SUOMEN GEOLOGINEN TOIMIKUNTA || GEOLOGISKA KOMMISSIONEN I FINLAND

BULLETIN
DE LA
COMMISSION GÉOLOGIQUE
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N:o 83

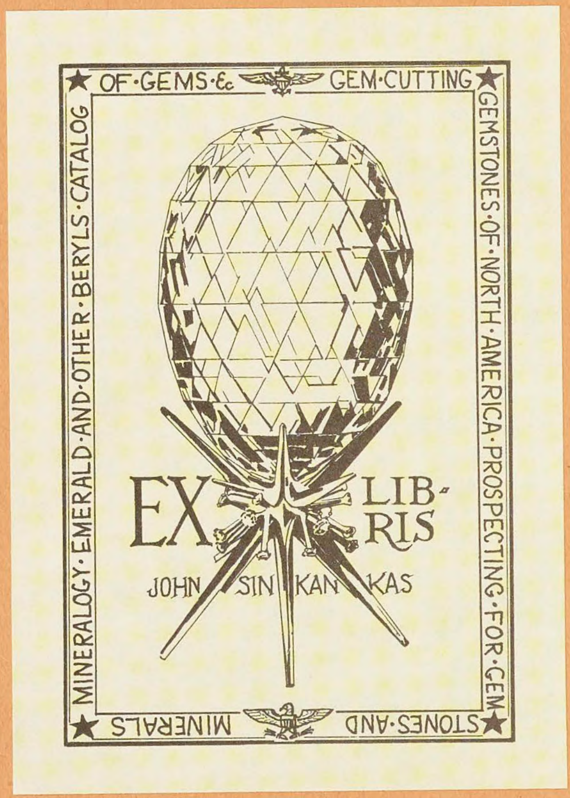
ON ORBICULAR GRANITES
SPOTTED AND NODULAR GRANITES ETC. AND ON THE RAPAKIVI TEXTURE

BY

J. J. SEDERHOLM

WITH 19 FIGURES IN THE TEXT AND 50 FIGURES ON 16 PLATES

HELSINKI — HELSINGFORS
SEPTEMBER 1928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PREFACE.

The writer is indebted to many colleagues who have assisted him in this work. Professor Hj. Tallqvist, Dr. V. Tanner, Dr. M. Sauramo and Mr. W. W. Wilkman have placed the new orbicular granites found by them at his disposal. Professor P. Eskola has lent him a specimen of the Pöytyä granite and Dr. Gavelin a stereotype of the orbicular granite of Stockholm. Professor J. M. Zujovic and Dr. W. Campbell Smith have sent him their publications on orbicular rocks. M. Alfred Lacroix has given him information on the alleged orbicular granites of France and on some Japanese orbicular rocks. Dr. V. Hackman has taken the trouble of calculating the analyses.

Mr. J. Meurman of Liuksiala Manor, and the Landowners' Association in Kangasala have been very active in securing some important specimens of the orbicular granite of Kangasala.

The author desires to express his most cordial thanks for all this valuable assistance.

Helsingfors, 15:th May, 1928.

INTRODUCTORY REMARKS.

The so-called orbicular granites, no doubt, belong to the most interesting petrological phenomena. Among granitic rocks which otherwise often show such a great monotony over wide areas, we here find structures that appear remarkable and beautiful even to the non-scientific observer and, as is already shown by their rarity, obviously represent very peculiar conditions of rock formation. If we succeed in interpreting them, we may, therefore, be able to throw considerable light on the crystallization processes of magmas solidified at a great depth. The physical conditions determining their mineral composition and texture, the differentiation processes, the movements which have taken place during the crystallization, etc., may be elucidated by such studies. We here meet with many of the main problems of granite petrology, almost literally, in a nutshell.

Earlier papers on orbicular granites, especially those of von Chrustschoff and Frosterus, have thrown much light on these structures. However, many phenomena still remain unexplained, and it may therefore be of interest again to take up the matter for discussion.

During the last decade four new orbicular granites have been found by officials of the Geological Survey of Finland, which seems to be the country that possesses the greatest number of such rocks in relation to its area. Of these orbicular granites many photographs have been taken both of the outcrops and of sawn and polished specimens. A fifth orbicular rock has been found in Finland by Professor Eskola. Many new slabs of the earlier known orbicular granites from Virvik and Kangasniemi have also been sawn and polished, and new observations have been made, too, on the outcrop of the former. The author has also studied all these rocks microscopically, and has had new chemical analyses made of some of them.

He will therefore give a short summary here of these new observations. The time at his disposal necessitates a certain brevity in the descriptions, especially of the microscopical features. His studies have, however, led him to new conceptions which he will here expound, concerning the origin of these peculiar structures. He will later also discuss some other structures of similar appearance or analogous origin. A description of the new occurrences will first be given.

ON ORBICULAR GRANITES.

THE ORBICULAR GRANITE OF PUUTSAARI IN JAAKKIMA.

During an excursion in the region near Lake Ladoga made by the author together with Dr. V. Tanner, Dr. V. Hackman and Dr. O. Trüstedt, in the year 1923, the granite quarry near the Greek-Orthodox monastery of the island of Puutsaari in the parish of Jaakkima was visited. Here Dr. Tanner found a small block of orbicular granite lying among the rubble in the quarry. The outcrop could not be found, but there is little doubt that the specimen was formerly part of the outcropping granite quarried.

Fig. 1, plate I, shows a polished surface of the only specimen of this orbicular granite which has been found. A medium- to coarse-grained granular rock forms both the nuclei of the spheroids, or rather ellipsoids,[1] which consist mainly of oligoclase, and the rock mass lying between them. In some places there is, at the inner or outer margin of the oligoclase shells, a greenish-grey zone which contains small flakes of biotite. Between the better developed ellipsoids there are others which show a more imperfect orbicular structure: portions of the granitic rock are surrounded by an indistinct shell of plagioclase.

This orbicular granite belongs to the same class as the orbicular granites of Stockholm and Spitzbergen, described by Brögger and Bäckström (9, 12, 13).[2] All these rocks are very simple in structure and contain nuclei which are similar to the mass surrounding the spheroids.

THE GRANITE OF THE NEIGHBOURHOOD.

Before giving a petrological description of this orbicular granite, we will describe the granite of the island of Puutsaari in Lake Ladoga on which it occurs.

[1] The nomenclature applied to the rounded objects characteristic of the so-called orbicular granites is very varied. In Swedish and German, they are simply called »klot» or »Kugel» which corresponds to »ball» in English. But as they are seldom or never quite spherical in shape, they are more properly called spheroids or ellipsoids. In some cases, the word ovoid may also be appropriate. Lawson has proposed the term orboid, and orbicule has also been used. It would be convenient to have a special designation for these objects, so peculiar in appearance and also in origin, but as none of those proposed hitherto seems satisfactory, and the present writer has not been able to find any better one, the descriptive stereometric designations, especially spheroid and ellipsoid, may be alternately used, although they here seldom correspond with absolute exactness to the facts observed.

[2] The figures in parenthesis refer to the list at the end of the paper.

This granite, which occupies the greatest part of the island, has a composition which is rather different from that of the orbicular rock. While this is very rich in oligoclase, the red, porphyritic granite is rich in microcline. This mineral alone forms the porphyritic constituents which have a maximum size of 1 × 2 cm. Between them lies a greyish red mass of biotite, feldspar [1] and quartz.

The plagioclase, which is an oligoclase with 27 % An, forms smaller crystals which are always idiomorphic towards the microcline. The biotite lies between the feldspars. The quartz has strongly corroded the feldspars and is entirely xenomorphic towards the other minerals. Magnetite occurs in some places between grains of quartz. Muscovite has in some places been formed within the feldspars as a deuteric constituent. Small crystals of zircone occur in the biotite, and are surrounded by pleochroic halos.

Medium-grained varieties of this granite also occur in the neighbourhood, and are in part red, in part grey. In some of them oligoclase is abundant, and has been corroded in the most typical way before the crystallization of the microcline, while the last crystallized quartz has again corroded both feldspars. The oligoclase is sometimes antiperthitic. Some of these granites are aplites which are almost free from biotite. Garnet occurs sparsely in the form of small crystals, lying in all the other minerals.

The Puutsaari granite resembles, on the one hand, the Perniö granites of southwestern Finland, which are porphyritic equivalents of the Hangö granites. These belong to the second group, of the classification of the granites of southern Finland which has been made by the present writer. On the other hand, the Puutsaari rock also resembles certain porphyritic granites of the third group, which is represented in south-western Finland by the Obbnäs, Onas, Åva, Mosshaga and Lemland granites (79, 81—83).

It is rather difficult to decide to which of these two groups the Puutsaari granite belongs. It is certainly somewhat later in age than the grey granites which occur in the same island and in the adjacent coast regions of Lake Ladoga, and which intimately interweave Archæan schists, forming with them migmatites. Among these migmatites some occur, e. g., on the island of Vaavasaari, N. of Puutsaari, that resemble granitized conglomerates or breccias. They are very polymict, and the inclusions have varying sizes. Some of them are angular, others well rounded. The present writer was formerly

[1] The reason why the spelling feldspar has been here preferred to felspar will be given later on, at the description in the rapakivi granite.

inclined to regard these peculiar rocks as real conglomerates which had been strongly granitized, like those that he has described from the Pellinge area (80, pp. 128—137).

It would, then, be most natural to correlate them with the conglomerates of Kalevian type which occur in neighbouring regions. Under this assumption, and also because of the similarity of the Puutsaari granite to granites that certainly belong to the third group, the writer referred the present granite to this group (79), to which he reckons also the post-Kalevian granites of northern Finland.

Later, however, he found that the conglomeratic character of the rock of Vaavasaari is more than doubtful. Some of the inclusions are very big, up to 1—2 m in diameter, and there seem to be gradations towards typical eruptive breccias, with angular fragments cemented by granite. Moreover, the Puutsaari granite lacks some of the characteristics of the porphyritic granites of the third group of south-western Finland, such as the content of fluorite, while it occasionally contains garnets which have so far not been observed in them. Their areas are also more sharply defined, while the present granite has diffuse boundaries. It is, therefore, equally possible that it originated by the latest eruption of the granites of the second group which are common in the adjacent regions.

The Puutsaari granite is often entirely massive (homophanous). It occasionally contains a great number of fragments of older rocks which have been more or less completely changed and in part assimilated. Among them basic and ultrabasic rocks occur, but also gneissose granites and migmatites have been intimately penetrated by the same granite. In some cases, the fragments have been soaked with granitic magma to such a degree as to lose their former composition, so that they gradually fade away, becoming more and more similar to a granite in composition.

Some portions of the granitic masses of this island may thus also be defined as eruptive breccias. The rock which has been quarried is more uniform in composition, but it also contains fragments of basic rocks.

THE ORBICULAR ROCK.

As already stated, the orbicular granite of Puutsaari has a chemical and mineralogical composition which is quite different from that of the surrounding granite. It is very rich in plagioclase which forms the greatest part of the ellipsoids. These have a very simple structure here. Around the nuclei, consisting of the same granitic mass as lies between the ellipsoids, there are shells consisting mainly of plagio-

clase, which is preponderantly arranged as radiating needles or stalks, in the same way as in the spherulites of quartz-porphyritic rocks. Grains of quartz occur in the shells, sometimes also minute flakes of biotite. In some cases, a shell next to the granitic core is somewhat richer in biotite than the other parts and is then darker in colour. One ellipsoid lying between the three bigger ones, to the right in the figure, consists of a core of feldspar surrounded by a very indistinct shell of darker minerals. This ellipsoid has a certain analogy to the smaller ellipsoids in one of the varieties of the orbicular granite of Virvik.

Microscopically, the present rock shows very characteristic peculiarities.

The rock between the ellipsoids is rich in oligoclase (An 29—30) which is often highly idiomorphic, although partly showing forms indicating corrosion. Microcline with beautiful lattice lamellation occurs, partly in parallel intergrowth with the plagioclase, partly independently, surrounding it and then showing xenomorphic forms towards it. Even towards the quartz it may sometimes be xenomorphic. In general, the quartz which is almost free from signs of stress, is, however, quite xenomorphic, especially towards the plagioclase which occasionally has been strongly corroded. The biotite commonly lies between the feldspars, but may also encroach upon them, then often occurring in myrmekite-like intergrowth with quartz. Muscovite occurs in the form of flakes, which often show a fringed margin, and is accompanied by calcite (fig. 1, plate XIII). Both minerals are late constituents which have replaced parts of the feldspars that have been dissolved by gases.

The granitic core has a composition similar to that of the cement. The plagioclase may be very strongly corroded. Both the quartz and the biotite occasionally form bigger crystals.

The shells of the ellipsoids are mainly composed by oligoclase (An 30) and quartz, with sparsely interspersed minute flakes of biotite. The plagioclase is mostly radially arranged (fig. 2, plate XIII), but the needles are not always elongated in the same direction, but may have grown along the vertical or the clino-axis, according to the position which the first germ of the crystals possessed. Between them lie drop-like small grains of quartz. They are often enclosed in the feldspar, obviously being earlier in date, while, in other cases, the feldspar has been corroded when bordering on quartz. Probably both minerals have crystallized simultaneously, and a small advantage, at the end of the crystallization, of the one or the other may have caused differences in their delimitation. This intergrowth differs, however,

very much from the micropegmatite through the imperfect crystallization of the quartz.

The quartz contains minute needles of a birefringent colourless mineral which is probably apatite.

As we find very similar features in the other orbicular rocks, too, but in still more typical forms, we may postpone their discussion till these have been described.

THE ORBICULAR GRANITE OF ESBO (NUOKS LÅNGTRÄSK).

A very interesting orbicular granite was discovered by Dr. Hj. Tallqvist, Professor of Physics at the University of Helsingfors, who called the attention of the present writer to this rock. He feels much indebted to the discoverer, because this orbicular granite is extremely interesting, as it unites many of the peculiarities of several other occurrences.

OBSERVATIONS IN THE FIELD.

This orbicular granite outcrops at a new road which is being built along the eastern coast of a lake called Nuoks Långträsk in the parish of Esbo, leading to Herrbacka in the northernmost parts of this parish. This road will in the future be continued into the neighbouring parish of Vihti.

About 3 km S. of Herrbacka, S.E. of a meadow called Koivulan Niitty, the road crosses a hill of granite which is partly covered by morainic deposits, but partly lies exposed. Along the road and at the eastern side of it, the orbicular granite outcrops in an area which measures about 80 m in a N.W. direction and about half that distance in the direction E.—W.

The prevalent rock in the surrounding region is a greyish granite of medium grain which sometimes becomes indistinctly porphyritic. It is a granite rich in microcline, belonging to the same group as the Hangö and Ingå granites which have been described in former papers (80, 82). They possess in general, when they are free from inclusions, a rather uniform chemical composition.

The rock masses which show the orbicular structure have, however, a peculiar chemical composition, being very rich in oligoclase and mostly also in biotite.

In the greater part of the orbicular rock the spheroids, which are also here partly ellipsoidal in form, have a diameter of 6—15 cm and consist of a lighter nucleus and a dark shell, sometimes showing a distinct lamellation. There is another variety in which the spheroids

are small, measuring only 2—3 cm, and consist mainly of an aggregate of coarse feldspar grains surrounded by a dark cementing mass, rich in biotite. Fig. 1, plate III, shows this rock in contact with the variety with bigger spheroids.

In a few cases, the bigger spheroids contain a nucleus of a schistose metabasite (fig. 2, plate I) surrounded by a zone rich in feldspar.

The dark patches in one of the spheroids in fig. 1 are probably also remains of such a fragment, although it has been in great part destroyed by the dissolving action of the magma.

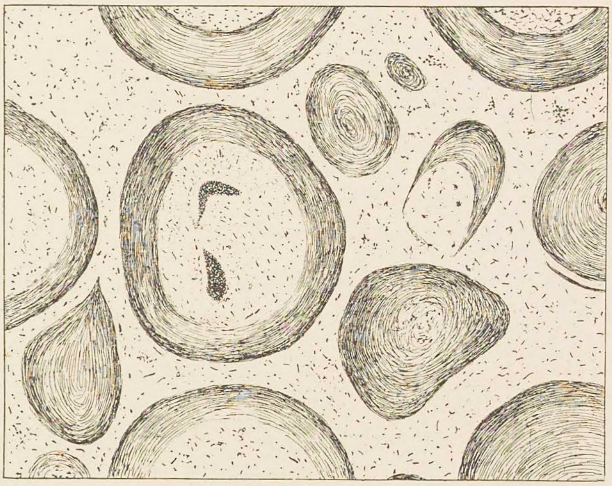


Fig. 1. Spheroids of which one contains remains of dissolved fragments of foreign rocks. Nuoks Långträsk, Esbo. 1/4 nat. size.

The spheroids are rather varied in shape, often regular and well rounded, in other cases, again, deformed by the impact of adjacent spheroids, in part also broken in pieces. (Cf. the figs 1—3, in the text, and figs 2, plate I, and 1—2, plate II).

In fig. 2, we observe, between the bigger spheroids, one which is small and has a simple structure.

Before taking the photographs of the surfaces of the rock, the latter were wetted. They then show the structures almost as well as a polished surface. Moreover, several specimens were sawn and polished, and these are shown by fig. 3 in the text and fig. 1, plate II.

The contact between the orbicular rock with big spheroids and the one with the small ones is fairly distinct.

In some places in the orbicular rock, and also in the neighbouring granite, bigger fragments of metabasite occur. They have in part

been rounded by resorption and are surrounded by aureoles consisting of a mixture of granite and refused, assimilated amphibolitic constituents. In fig. 4, there is a double aureole, the inner portion very nearly possessing the composition of the core of the fragment, while the outer zone is pale and approaches a granitic composition. At the outer margin, the aureole is again darker, basic material having

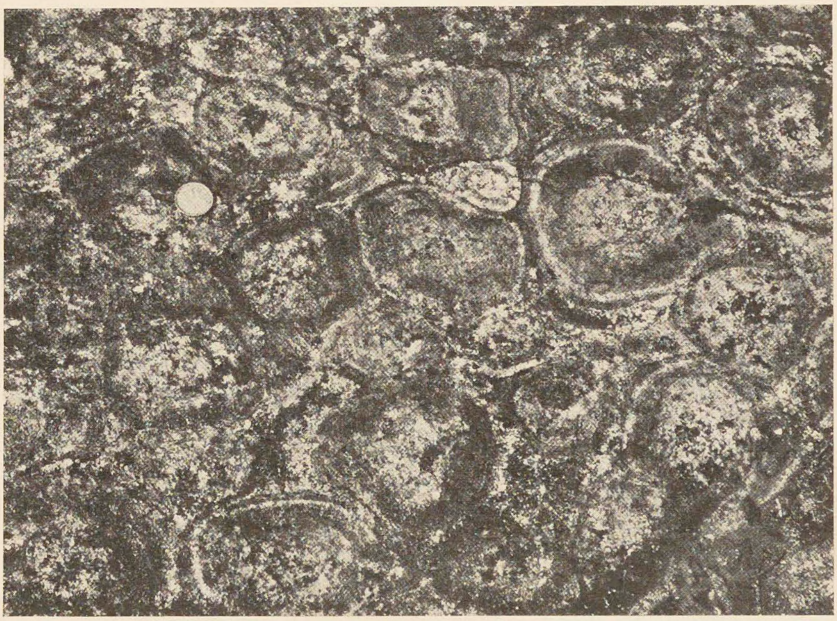


Fig. 2. Orbicular granite with bigger spheroids and one small spheroid. Nuoks Långträsk, Esbo. 1/4 nat. size.

obviously been spread by diffusion as far as the outer boundary of the lighter zone. Fig. 2, plate II, shows another bigger elongated fragment which is of great interest. As we are aware from the figure, it is surrounded by an aureole of minerals which have been formed by a syntexis of the metabasite and the surrounding granite (cf. 82, pp. 101—108). This aureole shows the same differentiation into darker and lighter zones as some portions of the mass between the spheroids. Both phenomena must be due to the same cause, which is obviously to be defined as a kind of fractional crystallization, by which biotite has crystallized mainly at the margins, feldspar preponderantly in the middle of the aureole. The darker outer zone has even penetrated between the adjacent spheroids, and these have made impressions on it, which shows that it was partly fluid at a

very late epoch. Consequently, there was a zone of fluid matter next to the fragment when the spheroids had already been formed.

It is of great interest to note that the quasi-centric structure of the fragments surrounded by aureoles shows no direct connection with the formation of the true spheroids. These lie alongside the

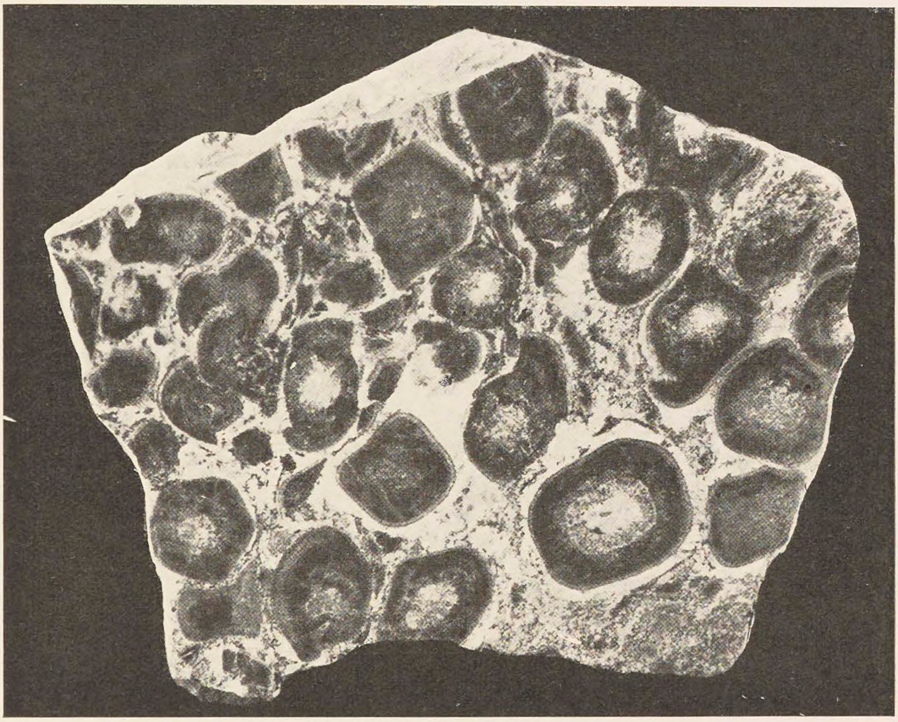


Fig. 3. Orbicular granite with some well developed spheroids and others which are deformed and brecciated. Nuoks Långträsk, Esbo. C:a 1/8 nat. size.

fragments, even encroaching upon their aureoles (fig. 2, plate II), but there is no indication of a gradation between these structures which are obviously genetically different, although no doubt smaller fragments have, in some cases, formed the cores of certain spheroids.

Fragments of mica-schists also occur which have been mixed up with granitic veins, so that typical migmatites have originated. Some small, but indubitable spheroids are seen inside the margins of a migmatitic fragment (fig. 2, plate III). This fact definitely proves that the formation of the spheroids, in this case, has taken place independently of the brecciation of the rocks forming the fragments.

At a first glance, the spheroids look fairly uniform, but on a closer inspection we find that many of them contain portions that

are rather different in composition and texture. The innermost core is commonly rich in feldspar. Nearer to its outer margin, there is often a shell containing a little more mica which may occasionally show an indistinctly radial arrangement. Then there often follows a zone consisting of plagioclase laths that are radially arranged, but are mixed with more or less biotite. The outerlying, main portion of the shell has an almost black colour and consists of small crystals of biotite and feldspar. These shells show a zonar structure which is, however, often rather indistinct. Finally we observe, again, in some cases, an outermost shell which is lighter and richer in plagioclase.

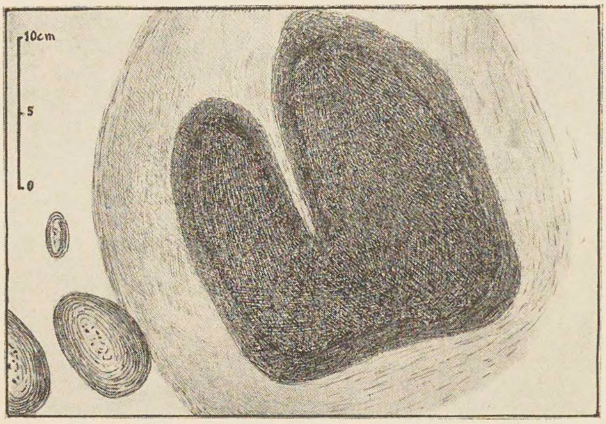


Fig. 4. Fragment of a basic schistose rock which has been partly dissolved and is surrounded by an aureole. Nuoks Långträsk, Esbo. 1/5 nat. size.

As shown by the photographs, there is, however, no very great regularity in the behaviour of these different portions of the spheroids, but they show many individual variations.

CHEMICAL COMPOSITION.

The impression conveyed by the photographs is that the composition is very different in the matrix and in the dark shells. Analyses have been made of both of them (Tables I—II); they show, however, that the differences are only very small. Both the shells of the spheroids and the cementing mass have a composition near to that of dioritic rocks, however with a very high content of plagioclase. The darker colour of the spheroids is mainly caused by the finer distribution of the biotite, just as snow mixed with a small quantity of coal dust may appear almost black.

The cementing mass between the spheroids is on an average rather uniform in composition, but it often shows a zonar distribution of the minerals, with feldspar mainly at the sides and biotite preponderantly in the middle. Where the spheroids lie near to each other, the biotite which has filled the last residuals may form veinlike stripes which are almost black (fig. 2 in the text and fig. 1, plate II).

The uniformity, in the main, of the chemical and mineralogical composition of all the different parts of the rock makes the problem here simpler than in many other cases, thus eliminating some of the explanations given for similar structures which are based on the assumption that very great differences between core and shell, or between the spheroids and the surrounding mass, always exist. Here we have only to do with the following proposition: given a crystallizing magma whose composition is that of a »dioritic» rock very rich in plagioclase, how do we account for the aggregation of its minerals into these peculiar structures?

Table I.

Dark shell of a spheroid in the orbicular granite from Esbo. Analyzed by Lauri Lokka.

	%	Mol. prop.		
SiO_2	56.13	935	or	13.34
TiO_2	1.86	24	ab	48.73
Al_2O_3	22.15	217	an	27.80
Fe_2O_3	0.79	5	Sal	89.87
FeO	3.62	50		
MnO	0.01	—		
MgO	0.43	11	di	0.71
CaO	5.80	104	hy	3.51
Na_2O	5.74	93	mt	1.16
K_2O	2.34	24	Il	3.65
P_2O_5	0.06	—	Fem	9.03
$H_2O +$	0.57	—	S:a	98.90
$H_2O -$	0.15	—		
	99.65			

C. I. P. W.: I, 5, 3, 4. Yellowstonose.

Niggli: si 183 al 42.5 fm 14.0 c 20.5 alk 23.0 k 0.20 mg 0.15 ti 4.7 qz —9 c/fm 1.46.

Table II.

Cementing mass between the spheroids in the orbicular granite of Esbo.

Analyzed by Lauri Lokka.

	%	Mol. prop.		
SiO_2	57.26	954	Q	1.68
TiO_2	1.08	14	or	11.68
Al_2O_3	23.64	231	ab	50.83
Fe_2O_3	0.39	3	an	27.52
FeO	2.45	34	C	1.43
MnO	0.01	—	Sal	93.14
MgO	0.11	3		
CaO	5.72	102	hy	2.54
Na_2O	6.00	97	mt	0.70
K_2O	1.96	21	il	2.13
P_2O_5	0.09	1	ap	0.34
H_2O + ...	0.76	—	Fem	5.71
H_2O —	0.15	—	S:a	98.85
	99.62			

C. I. P. W.: I, 5, 3, 4. Yellowstonose.

Niggli: si 196 al 46.5 fm 8.5 c 21 alk 24 k 0.18 mg 0.07 ti 2.9 qz ± 0 c/fm 2.46.

If we take the arithmetical average between the two analyses, we get the following composition of the rock as a whole.

Table III.

SiO_2	56.91
TiO_2	1.47
Al_2O_3	22.97
Fe_2O_3	0.59
FeO	3.05
MnO	0.01
MgO	0.27
CaO	5.78
Na_2O	5.89
K_2O	2.16
P_2O_5	0.08
H_2O + ...	0.67
H_2O —	0.15
S:a	100.00

MICROSCOPICAL DESCRIPTION.

THE GRANITE OF THE NEIGHBOURHOOD.

The greyish granite of the neighbourhood, such as it outcrops, e. g., in the rocks N.E. of the orbicular granite, has a character which is very common among the granites of the Hangö type. It is rich in quartz, and microcline preponderates over the oligoclase. The last-mentioned mineral has crystallized earlier than the former. Myrmekite is common at their mutual boundaries. The quartz, which has an undulatory extinction, but is not divided into portions with quite different extinction, has everywhere strongly corroded the feldspars. Biotite is, perhaps, a little more abundant than is usual in these granites. It is in great part xenomorphic.

Garnet is here absent or at least very rare, but it often occurs in other places in the granites of the region as small crystals and is occasionally very abundant.

Small crystals of epidote occur and are, when included in the biotite, surrounded by pleochroic halos.

THE ORBICULAR GRANITE WITH SMALL SPHEROIDS.

The very indistinct spheroids in the variety with small spheroids are mainly composed by feldspar and biotite. Plagioclase prevails, and is an oligoclase with 32 An. The individuals have varying sizes, and their forms are very irregular. Their outlines are often dentated (cf. fig. 3, plate XIII). Sometimes the bigger crystals enclose a number of smaller patches of the same mineral. Microcline is present in varying quantities, sometimes in parallel orientation with the plagioclase, sometimes, again, quite xenomorphic against it. The quartz is always quite xenomorphic, and has often corroded the other minerals. The biotite is in some cases decidedly idiomorphic, but in other cases, again, it fills the interstices between the feldspars and is entirely xenomorphic.

THE VARIETY WITH BIGGER SPHEROIDS.

T h e n u c l e i of the bigger spheroids have in general the same composition as the small spheroids. Oligoclase prevails among the constituents. It forms crystals with a fairly irregular delimitation, often with very sinuous boundaries, even where they border on other oligoclases. The microcline, which occurs in varying quantity, has sometimes the same optical orientation as the plagioclase, but more often it is xenomorphic, in many cases also towards the plagioclase (cf. fig. 4, plate XIII). Occasionally, numerous crystals of plagioclase are included in the microcline (cf. fig. 5, plate XIII). The quartz

has a feebly undulating extinction, but has not been divided into grains with varying optical orientation. It is entirely xenomorphic towa ds the feldspars, also the plagioclase (fig. 6, plate XIII), which it has sometimes strongly corroded. The biotite has the same character as in the cement which which will be described below.

Crystals of a pleochroic epidote are often very numerous and especially occur in the biotite or near to it. Also, when it is included in the plagioclase, it is somewhat doubtful whether it is really older than that mineral. Next to the epidote crystals, the biotite shows very marked pleochroic halos. Occasionally, although rather rarely, slender crystals of zircone occur. The dark haloes around them are not quite so well developed as those which surround the epidotes. Apatite crystals occur in varying quantities. In some biotite crystals, small grains of fluorite have been observed.

T h e d a r k s h e l l s mainly consist of a fairly equigranular mingling of plagioclase and biotite, in which the individual grains commonly measure less than 1 mm (fig. 1, plate XIV). The biotite is usually idiomorphic, sometimes, however, quite xenomorphic. Small grains of microcline may sometimes occur next to the biotite crystals (fig. 2, plate XIV), occasionally occupying the centre, while the biotite coats the walls. Microscopically, there is no distinct zoning in the distribution of the minerals.

Where the plagioclases are bigger in size, the small biotite crystals included in them are often less numerous.

T h e c e m e n t between the spheroids presents, microscopically as well as macroscopically, almost the same peculiarities as the core portions.

The microcline may occasionally have a decidedly xenomorphic delimitation. In fig. 3, plate XIV, we are aware of a grain of typical myrmekite that forms the continuation of an oligoclase crystal and protrudes into the microcline. There are peculiar antiperthitic implications of microcline and plagioclase (fig. 4, plate XIV).

The biotite is often quite xenomorphic (fig. 5, plate XIV) but it also occurs as small crystals included in the feldspars. Occasionally, it may occur at the boundary of a plagioclase crystal in symplectitic intergrowth with it (fig. 6, plate XIV).

Garnets sometimes occur both in the cement and in the core portions of the spheroids.

In general we find, microscopically as well as macroscopically, no marked difference in the mineral composition of the different parts of the orbicular rock. As to the texture, the shells are different from the other portions.

THE ORBICULAR GRANITE OF KANGASALA (KUOHENMAA).

During the building of a new road along the western shore of Lake Roine in the parish of Kangasala, a big boulder of an orbicular granite was found near to the farm of Vuorela in Kuohenmaa. In June 1922, Dr. M. Sauramo, assistant geologist of our survey, observed this beautiful rock and brought a specimen of it to Helsingfors.

Later Mr. J. Meurman, owner of Liuksiala Manor in Kangasala, kindly undertook to secure the remaining parts of the boulders for the museum of the Geological Survey. The ownership of the boulders was claimed by different persons who wished to use them for decorative purposes. Mr. Meurman brought the matter before the Landowners' Association in Kangasala which decided that the boulders, which were situated on a public road, should be given over to the Geological Commission, and themselves paid the cost of transport. By this intervention, Mr. Meurman and the Landowners' Association rendered an important service to petrology. The new boulder, when it arrived, was found to belong to a different variety of the orbicular granite than had been collected by Dr. Sauramo. The ellipsoids of the rock collected later were much bigger than in the variety found earlier. (Cf. the figs. 1 on plates IV and V). Both varieties, however, show so much affinity as to leave little doubt that they belong to the same rock. The outcrop of this orbicular granite has, however, not been found.

This rock from Kangasala is one of the most beautiful and interesting orbicular granites that have ever been discovered.

As we are aware, when looking at the photograph of a polished slab (fig. 1, plate IV) the variety with small spheroids has a great resemblance to the well known corsite from Corsica, but the spheroids are in part bigger than in this rock, and the rock from Kangasala shows a still greater variety of interesting phenomena.

DESCRIPTION OF THE VARIETY WITH SMALLER SPHEROIDS.

The spheroids are composed mainly of plagioclase and biotite, forming concentric shells which are in part sharply limited against each other, in part show transitional zones, in which both minerals occur together.

The spheroids have very varied forms. Many are ellipsoidal with three rather different diameters. They are easily detached (fig. 5) and then look like more or less flattened pebbles (fig. 6—7).

They are surrounded by a granular mass, also consisting mainly of feldspar and biotite. The spheroids prevail in volume, in the surface shown in fig. 1, plate IV, taking up 60 per cent.

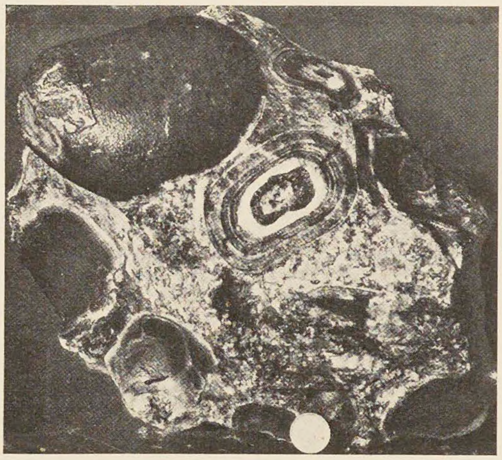
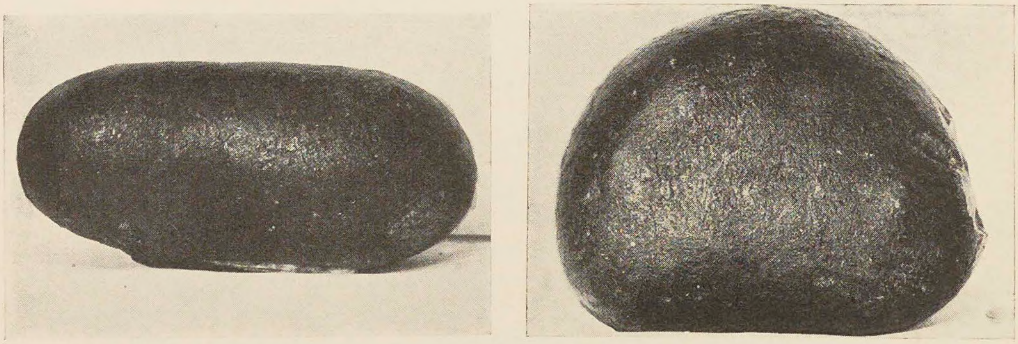


Fig. 5. Orbicular granite from Kuohenmaa near Lake Roine in Kangasala. 1/4 nat. size.



Figs. 6 and 7. Spheroids detached from the orbicular granite from Kangasala. 1/3 nat. size.

THE NUCLEI.

The nucleus of each ellipsoid may consist either of plagioclase, of biotite, or of an accumulation of both minerals. A few of them consist of almost pure biotite which does not form, however, one single crystal, but an aggregation of grains orientated in different directions.

In some of the spheroids, the nuclei consist of a rock showing a distinct schistosity. They are probably small fragments of rocks of different origin. They are occasionally surrounded by shells consisting of almost pure biotite, which are, however, not always quite continuous on all sides of the fragment.

In the spheroid shown in the right part of fig. 1, plate VI (A), the innermost core consists of an aggregation of irregular crystals

of biotite, intermingled with sparse grains of plagioclase. Then follows an indistinct shell, in which plagioclase is preponderant. At both ends of this innermost core, there are calottes, crescent-like in the section, consisting of biotite. The form is not such as to give the impression that these two biotite calottes are the broken parts of one shell that has formerly been continuous, but it seems more probable that they have formed incomplete shells from the beginning.

In the ellipsoid shown in the upper part of fig. 1, plate VI (B), there are several different nuclei. One of them, seen in the lowest part of the figure, consists of an aggregate of biotite and plagioclase crystals in almost equal quantity, while another, which lies to the left at the upper side, has a more complicated structure. It shows a dark zone, very rich in biotite, near the centre, another zone consisting mainly of feldspar, and an outermost zone rich in biotite. To the right of this nucleus, there are more irregular aggregates of biotite and plagioclase which seem to form three different nuclei. In the middle of them there is a fairly big crystal of pyrrhotite. All these different small nuclei unite into one composite nucleus which is surrounded by a continuous shell of plagioclase.

In the ellipsoid shown to the right in the lower part of the figure mentioned (C), the core consists mainly of plagioclase, with some biotite in the middle part. The first continuous shell here consists of almost pure biotite, the individual crystals of which do not lie with their cleavage parallel to the periphery of the shell, but, on the contrary, are arranged mainly radially, although in varying positions. At the outer surface of this biotitic shell there are, however, minute flakes of biotite which lie along the periphery, and so do the small biotite crystals in general in the outer shells. This difference in the behaviour of the biotite crystals of different sizes is an item of great importance.

As a polished specimen shows only one section through the rock, it is difficult to know exactly where it cuts the centres of the ellipsoids. The white central portions in some of the ellipsoids shown in fig. 1, plate IV, may in some cases be sections through shells which have surrounded a biotite core. When shells are broken with the hammer, it is, however, possible to prove that the nuclei are really in some cases preponderantly feldspathic.

These nuclei, or nucleus-like inner shells of plagioclase, occasionally show a radial structure. They are in some cases somewhat asymmetric, minute biotite flakes occurring as inclusions only at both ends, while the feldspar at the sides is free from them. Cf. the second from the left among the lowermost ellipsoids on fig. 1, plate IV.

This phenomenon is not casual, but we find it repeated at several places. It has probably the same explanation as the occurrence of the biotite calottes shown in fig. 1, plate VI (A), at the ends of the spheroids.

It seems rather difficult to account for the rounded shape of the innermost biotitic cores. They are not composed of one single rounded crystal, as is the case with the feldspar nuclei. Nor is there, in general, any sign of a radiating arrangement of the individual biotite crystals. Moreover, the rounded form is not quite perfect, but there are irregularities reminding one of resorption cavities. In fact, we find that the outer contours of the biotite crystals show forms which seem to prove that they have undergone resorption. Cf. the ellipsoid near the middle in fig. 1, plate IV. As the magma surrounding them contained mainly plagioclase, it is not surprising that it has been able to corrode the preexisting crystals of biotite.

The rounded form of the feldspar cores calls for a different explanation. We will return to this question later on.

In some cases, again, the cores of the spheroids consist of an aggregate of grains of feldspar and biotite which is rather similar to that of the mass surrounding the spheroids. In them a centric structure is only very indistinctly visible.

THE SHELLS.

When comparing the different ellipsoids visible in fig. 1, plate IV, we are aware how individual they are in size, shape and composition. In general, the innermost parts show the greatest contrast in the composition of the different shells, but there are also ellipsoids in which the inner portions show a lesser difference between the constituents, while there is a very marked contrast in the outer shells. In some ellipsoids we find a very simple structure, only four or five shells being distinguishable, while there are others in which 20 or more shells of different composition may be counted. Some shells show a greater variety in their composition, while others are fairly uniformly composed of dark zones, apparently richer in biotite.

There is an obvious connection between the formation of zones of purer biotite and those of purer feldspar. Almost in every place where we find zones of very pure biotite, whether it be in the middle of the ellipsoid or in some of its shells, the next shell of feldspar is very pure, and the limit is very sharp. On the contrary, the limit between the same feldspar shell and the next shells rich in biotite is not sharp, small flakes of biotite becoming gradually more numer-

ous. The phenomenon shows a certain formal analogy to the stratification of the glacial clays. The sandy portion, formed in summer time, of each annual layer is sharply defined against the clay of the preceding winter layer, while it shows a gradual transition upwards into the following clayey winter layer. In the present case, the feldspar corresponds to the sandy material of the glacial clays, and it is also more abundant than the biotite which corresponds to the clayey winter layer. The analogy lies in the fact that there is a marked r h y t h m in the deposition of the layers. When the crystallization of the biotite had gone on till all the supply of this material had been exhausted, in the neighbourhood of this shell, then mainly feldspathic material was available, and now began to crystallize. The change in the composition had been so complete that this feldspathic magma was even able occasionally to corrode the biotitic shell. When, again, the crystallization mainly of feldspar had continued for a while, and the neighbouring magma began to be exhausted of its content of this compound, then small flakes of biotite gradually began to crystallize and settle upon the ellipsoid, and their crystallization became more and more abundant.

Just as there are incomplete shells of mica forming calottes at both ends of the ellipsoid, so at one place also a shell consisting mainly of feldspar occurs which forms a calotte at one end and is not continuous all over the ellipsoid.

The outer delimitation of the ellipsoids is in general very sharp, especially when the outermost shell is biotitic. However, there is often a rim rich in oligoclase, and then some of the feldspar grains of the surrounding mass may be direct continuations of certain feldspars belonging to the shell, making its delimitation indistinct.

THE CEMENT.

The mass surrounding the spheroids has a granitic grain, and consists mainly of plagioclase, microcline, biotite and some quartz.

It is more abundant than in many other orbicular granites, where the ellipsoids often lie close to each other. Here they are also partly in contact, but in many places wide intervals exist between them.

As we are aware, the composition of the matrix shows almost as great variations as the ellipsoids. Some parts of it are dark and very rich in biotite, while others are composed mainly of feldspar and quartz. Some portions are rather coarse-grained, so that they are nearing a pegmatitic texture.

DESCRIPTION OF THE VARIETY WITH BIGGER SPHEROIDS.

In the other variety of this orbicular granite, the ellipsoids attain a maximum length of 25 cm. In general, they show the same phenomena as those of the variety already described, in some cases, even in a still more typical form.

THE NUCLEI.

Several of the nuclei consist of fragments of foreign rocks. In the great deformed ellipsoid just below the middle of fig. 1, plate V, the nucleus consists of a schistose rock rich in biotite. It shows a parallel texture which is accentuated by indistinct veins. In the spheroid furthest to the left, in the lowest row, there is also a nucleus consisting of a schistose rock rich in biotite. The same is true of the ellipsoid on the extreme left in the second row from above. This nucleus presents several phenomena of great interest. The schistose fragment in the middle is surrounded by a shell of biotite which has suffered lesions at several places, especially at the upper end. Obviously a resorption from the side of the surrounding feldspathic layer has taken place. The fragment in the centre of the biggest spheroid at the middle of the slab has, too, been resorbed at one side, and here, again, more biotite occurs in the white zone at both ends than at the sides.

THE SHELLS.

The shells around the nuclei show the same rhythmical development as in the variety with small spheroids. In most of them, a broad white zone of almost pure feldspar is observed, but this zone is by no means the same in numerical order in all the different spheroids. In some of them, mainly micaceous shells lie inside this broad feldspathic zone. In other spheroids, again, there is within it another broad white zone, while the darker zones are fewer in number. Consequently, no common succession of crystallization in all the different spheroids exists, but they have been individual in their development.

DEFORMATIONS OF THE SPHEROIDS.

The deformations of the spheroids are, in this case, too, of very great interest. By the impact of some spheroids on their neighbours, the rounded form has been changed into one more irregular. This deformation has especially taken place in the outermost shell which seems to have been at that time more plastic than the inner one, but in many cases also the latter have been more or less

affected. The outermost shell has, however, at the epoch in question been a solid body, although retaining a certain amount of plasticity. At the left side of the biggest ellipsoid, at the centre of the slab, the whole outermost dark shell had been shaved away, and it seems as if a small lump of feldspar lying between this and the adjacent ellipsoid had been the instrument of destruction, having been squeezed between them as between two mill-stones. Other portions of the dark shell just mentioned have, again, been folded and thrust over the inner portions of the spheroid. Inside these overthrusts, fissures have been opened that were filled with magma from without. In several other spheroids we observe similar overthrust-like movements which have been accompanied by injection of magma, so that a kind of »auto-migmatite» in a small measure has originated. In some of the spheroids, small faults have originated by these movements, showing that the shells were solid bodies, although, on the other hand, soft foldings indicate a partly plastic condition.

THE CEMENT.

The crystallization of the spheroids has, also in this case, ended rather abruptly, and the matrix has solidified like a common granitoid rock, in part, however, showing a coarser, pegmatitic texture. The coarsest portions seem to have been the last to crystallize. This coarseness of the cement is an item of great importance, because it shows that the mother-liquor existing after the formation of the spheroids must have been very much diluted with water or water vapour. This may account for the sudden interruption of the formation of the spheroids, from the moment, when the magma had attained a certain dilution. The spheroids as well as, in certain cases, individual minerals, must have been freely swimming in this mother-liquor. Therefore, the individual spheroids could be pressed against each other and minerals lying between them be rubbed against adjacent spheroids.

CHEMICAL COMPOSITION.

The chemical composition of the different parts of the orbicular granite containing small spheroids is shown by the following analyses which have been made by Lauri Lokka.

Table IV.

Average composition of a spheroid in the orbicular granite from Kuohenmaa in Kangasala.

Analyzed by Lauri Lokka.

	%	Mol. prop.		
SiO_2	57.21	949	Q	2.34
TiO_2	0.49	6	ab	51.35
Al_2O_3	24.31	238	an	20.85
Fe_2O_3	1.30	8	or	11.68
FeO	1.87	26	C	4.49
MnO	0.05	1	Sal	90.71
MgO	1.39	34		
CaO	4.39	78		
Na_2O	6.07	98	hy	4.98
K_2O	2.01	21	mt	1.86
P_2O_5	0.12	1	il	0.91
H_2O + ...	0.76		ap	0.34
H_2O —	0.22		Fem	8.09
	100.19		S:a	98.80

C. I. P. W.: I, 5, 2, 4. Laurvikose.

Niggli: si = 181 al = 46.5 fm = 15.0 c = 15.0 k = 0.18 mg = 0.44 alk = 23.5 qz = —13 c/fm = 1.0.

The mode is according to the calculation made by Dr. V. Hackman, as follows:

Plagioclase $Ab_{70}An_{30}$	71.20
Muscovite	2.72
Biotite	19.74
Quartz	5.41
Apatite	0.30
	100.37

Table V.

Cement of the orbicular granite from Kuohenmaa in Kangasala.

Analyzed by Lauri Lokka.

	%	Mol. prop.		
SiO_2	65.57	1.087	Q	14.94
TiO_2	0.56	7	or	21.68
Al_2O_3..........	19.77	193	ab	42.44
Fe_2O_3..........	0.16	1	an	14.18
FeO	1.58	22	C	2.24
MnO	0.01	—	Sal	95.48
MgO	0.08	2		
CaO	3.03	54		
Na_2O..........	5.02	81	hy	1.85
K_2O	3.70	39	mt	0.23
P_2O_5	0.13	1	il	1.06
H_2O + ...	0.34		ap	0.34
H_2O —	0.20		Fem	3.48
	100.15		S:a	98.96

C. I. P. W.: 1, 4, 2, 4. Lassenose.

Niggli: si = 276 al = 49.0 fm = 6.5 c = 14.0 alk = 30.5 k = 0.32 mg = 0.04 qz = + 54 c/fm = 2.15.

The mode is, according to the calculation made by Dr. V. Hackman, as follows:

Plagioclase $Al_{70}\,An_{30}$	56.53
Microcline	11.84
Muscovite	6.33
Biotite	8.78
Quartz	16.67
Apatite	0.30
	100.45

The biotite from the darkest parts of the spheroids has been separated, with the aid of heavy fluids, and analyzed. It is probable that the material contained some muscovite and small amounts of plagioclase.

Table V.

Biotite from the orbicular granite with smaller spheroids from Kuohenmaa in Kangasala.

Analyzed by Lauri Lokka.

	%
SiO_2	36.59
TlO_2	2.46
Al_2O_3	20.03
Fe_2O_3	9.98
FeO	11.23
MnO	0.10
MgO	7.36
CaO	0.28
Na_2O	0.60
K_2O	8.53
P_2O_5	0.32
$H_2O +$	2.16
$H_2O -$	0.15
S:a	99.79

If we regard the rock as composed of 60 % of spheroids and 40 % of cement (cf. p. 21), we arrive at the following average composition of the whole rock:

Table VI.

	%
SiO_2	60.44
TiO_2	0.52
Al_2O_3	22.46
Fe_2O_3	0.84
FeO	1.75
MnO	0.03
MgO	0.87
CaO	3.84
Na_2O	5.64
K_2O	2.69
P_2O_5	0.12
$H_2O +$	0.59
$H_2O -$	0.21
S:a	100.00

MICROSCOPICAL DESCRIPTION.

Microscopically, too, this orbicular granite is, perhaps, more interesting than any other. Both the different varieties show so much affinity that it seems most practical to describe them together.

THE NUCLEI.

In those nuclei that consist of foreign rocks, a schistose texture is clearly visible. E. g., the nucleus shown in fig. 1, plate XV, is a micaceous schist containing quartz, oligoclase, biotite and muscovite. This nucleus is surrounded by a shell of coarse biotite in which the individuals lie in different orientations. Muscovite occurs both as small crystals in the biotite and especially at its margins, and is certainly in both cases younger than the biotite. When the nucleus consists entirely of biotite which has been corroded by quartz, we microscopically observe crystals of biotite with skeletal forms (fig. 3, plate XVI).

THE SHELLS.

The broad shells of purer oligoclase which we find both next to the dark nuclei and, in many cases, elsewhere too, possess almost always a very distinctly radial structure, the individual feldspars, almost exclusively oligoclase, forming laths or slender needles which are arranged in bundles, the small ends of which are pointing to the centres and often obviously starting from a point on the next foregoing biotitic shell, while their broader ends are directed outwards. In many cases, they are like sheaves consisting of a great number of very slender crystals. Some of these sheaf-like groups of crystals are so slender that they remind one of the feldspar needles of spherulites. It seems certain that they have an identic origin with these. Obviously, the crystallization has begun with the formation of fine radiating needles of feldspar which have gradually become thicker by growing to the sides, too. The first formed skeletal crystals have often been feather-like, being composed by Baveno twins the dividing lines of which were the axes of the skeletal crystal. While the twinning, also in the thicker crystals, is often, of this character, it follows again, in many cases, the longitudinal direction of the feldspars. The figs. 1—2, plate XV, give an idea of these beautiful and interesting phenomena. The broader shells consisting of purer feldspar often end abruptly, and the following layer rich in biotite may lie transversely on their ends (fig. 3, plate XV). In this case, not the slightest doubt can exist about the fact that the outerlying shell was deposited u n c o n f o r m a b l y upon the next innerlying. The feldspathic

layer continuing the succession outwards may then have a granular texture, differing from that of the broader shells of purer feldspar.

In other cases, again, the radially arranged feldspar crystals enclose a number of biotite crystals arranged in rows following the periphery of the spheroids. Here, consequently, the crystallization of the feldspars has not been interrupted by the formation of the biotitic shells, obviously because the femic layers out of which the latter were formed were so thin that the feldspars continued their growth through them. The feldspathic and the biotitic portions are anyhow, even in this case, as well separated from each other as are the warp and weft of a textile fabric (figs. 5—6, plate XV, and 1, plate XVI).

We also occasionally observe that well determined biotitic layers are gradually replaced by others in which the biotite crystals and feldspar grains are irregularly distributed (fig. 5, plate XV). This fact is of special interest, because it shows that the dark shells of the Esbo granite, which microscopically show no distinct zoning, are not in principle different from the well stratified shells of the rock from Kangasala.

The biotitic layers are occasionally rich in quartz, and they often contain muscovite which has crystallized after the consolidation of the other minerals. These have been strongly corroded by its formation. Quartz may also occur between the feldspars of the lighter shells.

In one of the spheroids in the variety with small spheroids, we observe, at the outer periphery, a shell consisting mainly of crystals of plagioclase, between which lies xenomorphic quartz. The crystallization of the plagioclase crystals has obviously begun from the zone rich in biotite and muscovite which is lying inside them, and they have grown outwards. After them follows again, at the boundary to the surrounding cement, a zone in which numerous biotite crystals have originally lain along the periphery. They have, however, in some cases received an irregular position (fig. 4, plate XV), probably by movements in the magma.

THE CEMENT.

The matrix between the spheroids is obviously much richer in microcline than the spheroids. This mineral is always quite xenomorphic, when bordering on the other minerals, except the quartz which is also quite formless. The oligoclase forms very perfect crystals and the biotite, too, is xenomorphic, when lying in microcline or quartz. Muscovite occurs as irregular crystals which may be idio-

morphic also towards the biotite, but are certainly of deuteric origin, having encroached upon the other minerals, when they were already solid. Biotite occurs in much lesser amount than in the spheroids.

Fig. 4, plate XVI, shows the microstructure of this rock.

THE ORBICULAR GRANITE OF HANKASALMI.

In August 1924, Mr. W. W. Wilkman, assistant geologist to the Finnish survey, found a boulder of orbicular granite in the parish of Hankasalmi, S.E. of the town of Jyväskylä in Central Finland. The boulder lay on a rock called Kivikangas, 4.5 km E.S.E. of the church of Hankasalmi, near to the road to the flour-mill called Hankamäki. The boulder was, according to Wilkman's journal, rounded and measured 1.2 m in length and 0.5 in thickness. It contained numerous small spheroids measuring 6—8 cm, with a light nucleus rich in feldspar, surrounded by shells 1—1.5 cm broad in which biotite was arranged as concentric rings. The other boulders on the same hill consisted of a coarse porphyritic granite, a granodiorite rich in biotite and a migmatitic gneiss, rich in granitic veins and containing garnets. A careful examination failed to detect more boulders of the orbicular granite, or its outcrop.

The outcropping rocks of the surrounding region are mainly granites, diorites and gabbros, all of which seem to belong to the same group of plutonic rocks.

The figs. 2 on plates IV and V show photographs, on different scales, of polished specimens of this orbicular granite.

As we are aware, the ovoids have diameters of 3 to 8 cm. On an average, they measure about 4 cm in breadth and 6 cm in length. They show a well marked outer shell which is dark in colour and rich in biotite, and an interior portion in which feldspar predominates. In most of the ovoids, a nucleus and three or four shells may be discerned, but they are not very regular in size or composition, exhibiting many individual differences. The nucleus consists of purer feldspar. Then follows another shell containing some biotite, a shell in which feldspar is again prevalent, and an outermost dark shell which is rich in biotite.

The ovoidal form is fairly perfect in some of the spheroids, while others show the deformations which are so common in orbicular granites. As we will learn from the micropetrological description, the deformation is, however, in this case of a different character than usual, having continued even after the crystallization of most of the constituents of the rock.

The matrix between the ovoids is rather coarse-grained, in part almost pegmatitic, and consists of plagioclase, microcline, quartz and biotite in proportions which vary to some extent in different places.

CHEMICAL COMPOSITION.

The average composition of the orbicular granite from Hankasalmi appears from the following analysis made by Mr. L. Lokka.

Table VII.

Orbicular granite from Kivikangas in Hankasalmi.

Analyzed by Lauri Lokka.

	%	Mol. prop.		
SiO_2	61.84	1.025	Q	8.58
TiO_2	0.43	5	or	19.46
Al_2O_3	20.57	201	ab	40.87
Fe_2O_3	0.26	2	an	21.13
FeO	2.45	34	C	1.22
MnO	0.03	—	Sal	91.26
MgO	1.02	25		
CaO	4.42	79		
Na_2O	4.82	78	hy	6.06
K_2O	3.27	35	mt	0.46
P_2O_5	0.13	1	il	0.76
H_2O +	0.62	—	ap	0.34
H_2O —	0.09	—	Fem	7.62
	99.95		S:a	98.88

C. I. P. W.: I, 5, 3, 4. Piedmontose.

Niggli: si = 224 al = 44.0 fm = 14.0 c = 17.5 alk = 24.5 k = 0.31 mg = 0.40 qz = + 26 c/fm = 1.25.

According to a calculation which Dr. V. Hackman has kindly made, the mode of the rock should be the following:

	%
Quartz	13.87
Plagioclase Ab 65 An 35	62.00
Microcline	2.77
Biotite and muscovite	20.62
Magnetite	0.39
Apatite	0.30
	99.95

MICROSCOPICAL DESCRIPTION.

The central feldspar consists in some cases of microcline which is usually strongly crushed and contains small grains of myrmekite arranged along the cataclastic zones (fig. 5, plate XVI). In other cases, again, the feldspar of the nucleus is plagioclase (oligoclase with 35 $^0/_0$ An) which also forms the main part of the feldspar surrounding the nuclei. It often forms radiating laths. Between the feldspar grains, biotite occurs which is often, especially when surrounded by microcline, quite idiomorphic. In some cases, it is obvious that the oligoclase and the biotite have originally alternated in such a way that the biotite has formed regularly dispersed crystals in the feldspar, as is often the case in other orbicular granites. The regularity has, however, been disturbed by later movements in the rock.

Quartz occurs in varying quantities, especially in the matrix, and is always divided into grains with different orientation, as usual in rocks which have undergone pressure.

Small crystals of apatite are common.

This orbicular granite differs from all others known to the present author by the fact that it shows the influence of fairly strong metamorphosing agencies. An intensive crushing of the minerals has taken place, at an epoch, when the rock had already solidified, and the mechanical changes have been followed by chemical ones, new minerals having crystallized mainly along the cracks in the minerals. These cracks have not the character of continuous shearing zones, dividing all the rock, but have originated by a crushing of the individual minerals. Although secondary (or deuteric) biotite has originated in a great measure, it does not show a parallel position over wide areas, but follows in general the crystallographic orientation of the primary mica. The varying orientations in the rows of mica which mark the rounded forms of the ovoids are therefore preserved, and a schistose texture has not originated (fig. 6, plate XVI). In some cases, only, where there are long continuous rows of mica, these may have become prolongated, with the same orientation, even outside the micaceous shells of the ovoids.

The delicate features of the original structure are everywhere well visible through the veil thrown over them by the secondary changes, or may at least be easily reconstructed. As the primary structures are so characteristic, we have here a rare opportunity of comparing them with the secondary features, and thus to follow the changes which the rock has undergone. This is otherwise difficult, by the study of granites changed into gneissose rocks, because their original textures are not very characteristic.

Chemically and as to its mineralogical composition, the rock has probably not been changed. If we classify the rocks mainly according to their relations to types of chemical equilibry, or, in general, their mineralogical composition, this metamorphic orbicular granite, no doubt, should be referred to the same type as it belonged to before the metamorphism. Anyhow, fairly strong changes have certainly taken place, but mainly as to the texture.

The only more important change in the mineral composition is the formation of myrmekite in great quantity, especially where the microcline has been strongly crushed. Fig. 5, plate XVI, shows a typical example of »mortar structure», characterized by the crushing of the microcline and the crystallization of numerous minute warts of myrmekite on the cracks originated. The soda contents of the myrmekite may have been derived from the plagioclase which was replaced by biotite.

The granitic rocks of the neighbourhood seem all to belong to the same genetical group, and it is, therefore, probable that the metamorphism which this orbicular granite has undergone, is to be regarded as a kind of autometamorphism, and not as due to metamorphic processes much later than the intrusion of these granites.

SOME REMARKS ON THE ORBICULAR GRANITE OF KANGASNIEMI.

The Kangasniemi rock is, perhaps, thanks to Frosterus' excellent description (29), the best known of all orbicular granites. Photographs of it have appeared in many petrological works, and the explanation offered by Frosterus seems to be pretty generally accepted.

The present writer has visited the place where the boulders of this granite occur, and has had new slabs sawn and polished. In the main, however, his observations only confirm those of Frosterus, and also his conclusions. Only in some points, the latter may be slightly modified.

As to this granite, it seems to be very certain that the ellipsoids have been formed around nuclei consisting of foreign rock. At the first glance at fig. 2, plate VI, or at the plates accompanying Frosterus' pamphlet, it is evident that the nuclei consist of a gneissose metabasitic rock, in part also a granite, around which the constituents of the shells have gathered.

However, although this conclusion seems so obvious as not to be avoided, the explanation of the origin of these spheroids presents one difficulty which makes this granite almost more puzzling than any other orbicular rock. That consists in the existence of zones of

a granular pegmatitic, or aplitic, rock mass next to the included fragments forming the core, and the strange fact that this zone has occasionally been fluid at an epoch later than the formation of the surrounding shells that consist mainly of radially arranged feldspars, in alternation with shells that are richer in biotite.

Frosterus thinks that there have been formed in the magma zones with a peculiar composition, surrounding the fragments, and that the formation of these magma zones, and their later crystallization, have been influenced by the convection of material in radial directions, outwards from the nucleus in process of dissolution. The zones consisting mainly of radially arranged feldspars, in most shells plagioclase, should thus have crystallized later than the »pegmatitic» zone next to the included fragment.

Fig. 8. Spheroid in the orbicular granite from Kangasniemi, in which the rock of the zone next to the fragment penetrates the outer parts of the spheroid. Drawn by Frosterus. 1/2 nat. size.

Frosterus has, however, noted the extremely interesting fact already referred to, that the feldspathic zones of the shell have been cut by a pegmatitic vein which anastomoses with the rather coarse-grained rock next to the included fragment, and at the same time unites with the pegmatitic »Schlieren» of the granite forming the cement between the ellipsoids (cf. fig. 8).

If this cementing mass has been fluid later than the shells of the ellipsoids, as Frosterus thinks certain, then the same must be true also as to the zone which lies next to the fragments in the core. Else it could not erupt through the shells and unite with the magma between the ellipsoids, in the same way as the forces of a besieged fortress make a sortie and join hands with relieving troops.

Therefore, it seems impossible to think that the layers consisting of radially arranged feldspars should have been deposited upon the

light pegmatitic zone lying next to the fragments at the centre. They have originally been deposited directly upon the fragment, but as the shells have not been absolutely rigid and tight, they have been permeated by magma, or magmatic ichor, that has continued to react upon the fragment at the core, dissolving it and forming a zone of magma next to it, just as there is formed, in frozen arctic seas, in the spring a strip of open water next to the shores. This resorption of the fragment at the core has been strongest at the end of the consolidation of the rock mass, because at that epoch a diluted magma, rich in water, silicic acid and potash existed.

Quite analogous phenomena have been described by Grenville Cole from the Irish orbicular granite from Mullaghderg in Co. Donegal (19). In that case, too, the zone of magma next to the included fragment has made eruptive sallies through the girdles of surrounding plagioclase, joining with the magma of the cement.

The Kangasniemi rock is interesting, too, because the different shells show a much more varied composition than in most other orbicular granites. According to Frosterus' description, most of the shells mainly consist of plagioclase of somewhat varying character, and quartz, with some biotite; in most ellipsoids, however, there is, near to the periphery of the ellipsoids, a broad shell where microcline forms more than half of the mineral components. This microcline shell is again surrounded by a shell consisting mainly of plagioclase.

There has, thus, at certain epochs, existed around the ellipsoids in formation a magma very rich in potash, by the crystallization of which these microcline zones have been formed.

The granite cementing the ellipsoids, too, shows a very varied composition and texture. Some portions consist of a grey granite of medium grain which is often fairly rich in biotite. Other parts consist of a very typical pegmatite which has a light brownish or yellowish colour. Frosterus describes them as veins of pegmatite, but calls them also, on one occasion, Schlieren.

They are, in some places, somewhat better individualized than in others, but they do not, in general, form any well defined veins. In many places, there is no limit at all between the pegmatite and the grey granite, but a very gradual transition. It seems obvious that both these rock varieties have crystallized out of the same magma.

Fig. 3, plate VI, shows a portion of the cement lying between big spheroids. Here the greatest part of the mass is pegmatitic, and we are aware that at one place feldspar crystals protrude with their free ends into a mass of quite xenomorphic quartz that has obviously filled a druse-like cavity. It seems certain that the last

residual part of the magma has been very rich in water, allowing the feldspar to crystallize almost in the same way as in a mineral vein.

This gives a simple explanation of the variations in grain of the different parts of the rock. In some cases, however, this variation is more apparent than real, since there are, in the greyish rock which looks like a medium grained granite, at places feldspars which measure several centimetres in length, but are so full of included grains of biotite that the mass looks as if it were medium grained.

ADDITIONAL OBSERVATIONS ON THE ORBICULAR GRANITE OF VIRVIK.

The orbicular granite of Virvik in the parish of Borgå has been well described before by Frosterus (28). A continued study both in the field and on a great number of slabs which have been sawn and polished has, however, added many new observations of great interest which will be described here.

THE VARIETY WITH SMALL ELLIPSOIDS.

The variety with small ellipsoids shows, as was pointed out also by Frosterus, a great range of different structures. In the prevalent variety, the spheroids generally have an inner core consisting of grains of feldspar. Frosterus has also observed one which consists of a feldspar crystal. In some cases, however, the core consists of almost pure biotite (cf. fig. 2, plate VII). Around the light core there are usually three shells of different composition. The innermost, which is a direct continuation of the core portion, is composed of a mixture of feldspar and dispersed crystals of biotite. Then follows a narrow zone consisting mainly of feldspar, a dark zone (which has a rather varying character in different spheroids) in which biotite prevails, and, in many, but by no means in all spheroids, an outermost zone rich in feldspar.

In some cases (cf. also fig. 1, plate VII, on the right) there is, also in the light central parts, so much biotite that they can be regarded as composed of two portions.

In the variety which is shown in the centre of fig. 1, plate VII, the structure is very much simpler. Around a core which contains more or less biotite that sometimes forms indistinct zones, there is mainly one single shell rich in biotite. The surrounding matrix is coarse-grained and has a pegmatitic character. Finally, there is a variety (on the left in fig. 1, plate VII) in which the aggregations of feldspar grains are much smaller and not well rounded. The cementing

mass between them is similar to that of the variety just described. The variety with small feldspars is very near to a common coarse-grained granite, although somewhat richer in plagioclase than they are generally.

These gradations between the variety with small spheroids and a porphyritic granite have also been described by Frosterus.

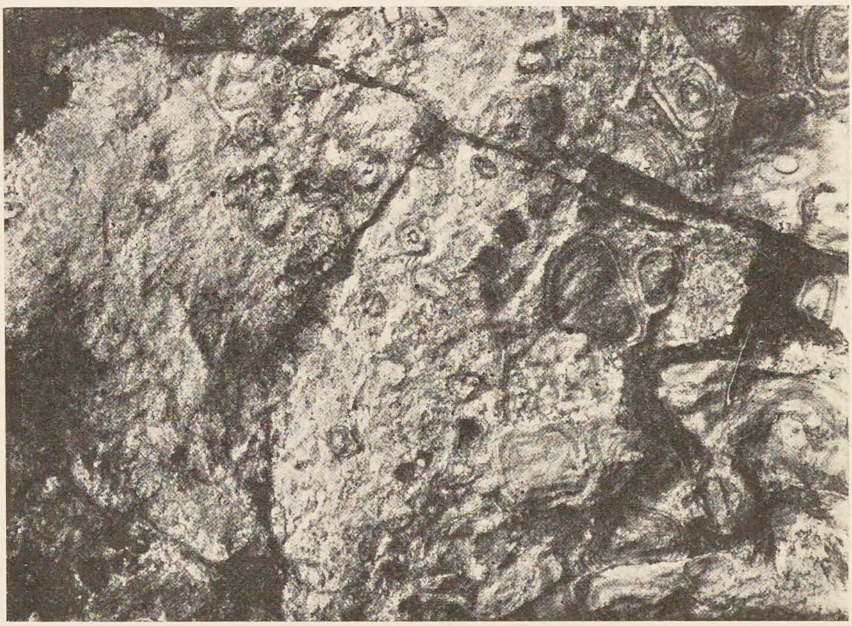


Fig. 9. Contact between the varieties with big and small spheroids in the orbicular granites contact, from Virvik, Borgå. 1/7 nat. size.

Fig. 1, plate VIII and fig. 9 show a very interesting phenomenon, the former in a polished slab, the latter in a vertical section of the rock, formed by its blasting. Portions of the rock with small spheroids were taken up in a later indruded granite, belonging, however, to the same series. The individual spheroids were to a great extent detached from the cementing matrix, most of which had probably already been solidified earlier, and became scattered during the flowing motion of the granite. In fig. 9 we observe the contact between this granite and the orbicular granite with big spheroids. These facts show that the small spheroids have existed as solid bodies at a time when a part of the granite was still in a fluid state.

RELATIONS BETWEEN THE VARIETIES WITH SMALL AND WITH BIG SPHEROIDS.

As we know already by the descriptions of Frosterus, all the beautifully developed spheroids of the variety with big concretions contain nuclei which are exactly like the spheroids of the variety with small ovoids. There cannot be the slightest doubt that the multiple shells of the big spheroids have gathered around small spheroids. In the same way as was shown, in fig. 2, to be the case with the granite of Esbo, a single small ellipsoid may sporadically appear, also in the Virvik rock, among the bigger ones (fig. 1, plate IX). The bigger spheroids of the surrounding rock, too, appear in this slab with very different diameters. This circumstance is not solely due to their being cut nearer to or farther from the centre, but partly also to the fact that they really have different sizes. The coexistence of the bigger spheroids and the lonely small spheroid may be accounted for either by its having originated much later than the rest of them, not having had time to reach its full development, or that it has, for other reasons, escaped the clothing with shells of alternating feldspathic and biotitic composition. If, as we will try to show later on, there have been fairly great differences in the composition of the magma in different places, it is by no means astonishing that there may survive, in an environment unfavourable to the formation of multiple shells, a single one retaining its simpler constitution, or, that in the cementing mass, in which in general the conditions favourable for the formation of the bigger spheroids have ceased to exist, there may be in some place still a possibility left for the formation of a single small ovoid.

In other cases, too, the ellipsoids of the variety with big spheroids show individual differences in their composition. Between spheroids of the most common type there may occasionally be found an isolated one, the shell of which is much darker, because the micaceous layers lie densely crowded. In the main, however, the big spheroids of the Virvik rock are mo e uniform in their original constitution than, e. g., those of the Kangasala granite.

THE DEFORMATIONS OF THE BIG SPHEROIDS.

One of the most interesting features of the Virvik granite is constituted by the deformations and lesions which the spheroids have suffered. These are especially conspicuous in the variety with big spheroids but, as Frosterus has shown, they are not entirely wanting, either, in the variety with small spheroids. There is hardly any spot in the former variety, where the spheroids have entirely escaped all

deformation. There is not the slightest doubt that, as Frosterus has already pointed out, the deformation took place before the final consolidation of the cementing mass. It is certainly not due to orogenetic pressure (Gebirgsdruck), as von Chrustschoff thought probable for similar phenomena. At the first glance at such a section as that shown in fig. 2, plate VIII, we realize that the spheroids which

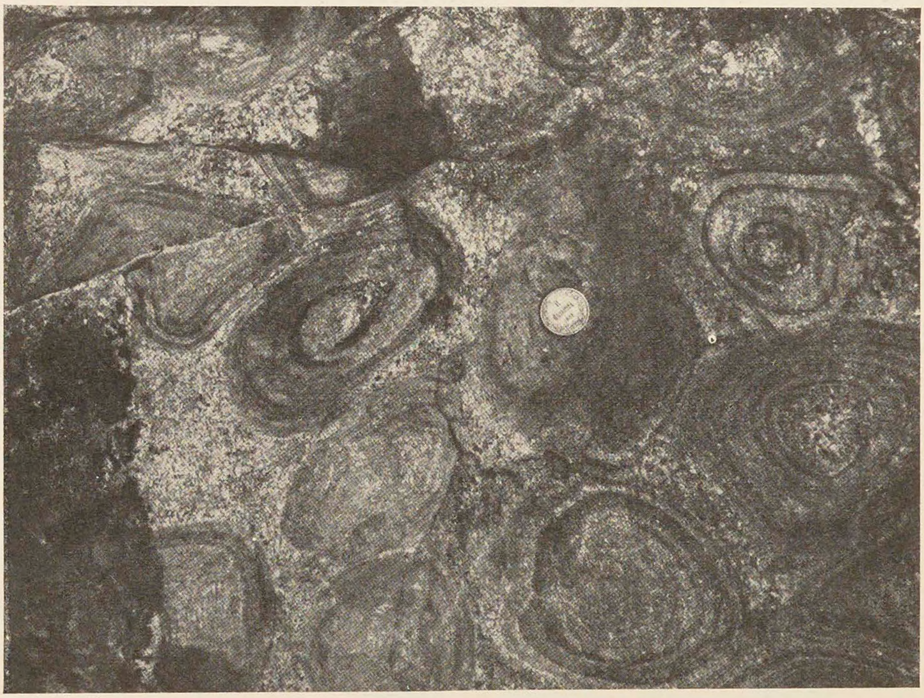


Fig. 10. Orbicular granite with spheroid which had been faulted at one side. Virvik, Borgå. 1/3 nat. size.

have suffered lesions were freely swimming in the cementing granite. Around spheroids from which a great part has been eroded away, light zones of aplitic granite wind, and between them the darker parts of the cementing granite are arranged. In the upper figure of plate IX a spheroid is seen that has been very much deformed at one side, obviously by the impact of a neighbouring spheroid. In fig. 10, one part of an ellipsoid has been faulted, while the other portion has been less influenced. In fig. 1, plate X, a spheroid is observed that has undergone a torsional movement, so that the nucleus and the surrounding shell no longer entirely fit each other in their forms. By that movement, openings, that have later been

filled up with feldspathic material, have been formed in the shell. This fact provides further evidence of the permeability of the shell to granitic magma or ichor. In fig. 2 of the same plate, the spheroid lying to the right shows similar lesions cemented by feldspar, while the left spheroid shows protuberances of the outermost biotitic shell that project between the nearest spheroids. They convey the impression that this outermost shell at the time of their formation was a kind of emulsion of small crystals of biotite in a gelatinous mass consisting of still at least partly fluid feldspathic constituents.

In fig. 2, plate IX, spheroids are observed that have suffered very strong lesions and deformations. What is of most interest here, is the fact that after these lesions new layers, consisting alternately of more biotitic and more feldspathic material, have been unconformably deposited upon the edges of the eroded older layers. This makes it evident, that the lesions occurred before the crystallization of the spheroids was ended, and removes the last doubt, if any exists, about the fact that their formation progressed from within outwards.

It seems unnecessary further to emphasize the above points. We may let the photographs teach their lesson, which is clear enough in itself without further interpretation, and only exhort the reader, while studying them, to call to mind existing theories, checking them by this new evidence.

There is only one question which it is still necessary to discuss, and that is the state of consolidation in which the spheroids were at the time, when they were deformed. They have obviously yielded very easily to the deformative movements. Adjacent spheroids have influenced the forms of their neighbours, although zones of granite separate them. Frosterus thought it possible that at the time of the changes only the biotite was crystallized, while all the feldspar still remained in solution. The present writer has also used a similar theory above as to the outermost layers rich in biotite. But this assumption, that they remained for a certain time in the state of an emulsion, only refers to the moment when the layer in question had been formed, as a zone of magma with a peculiar composition, and begun to crystallize. In general, the writer thinks, the greater portion of each shell had been consolidated before the next shell was deposited. The deformations of the spheroids are such as have taken place in a solid, but not yet entirely stiff and rigid medium. There is no contradictio in adjecto, in this, for, although the greater part

of the minerals of the spheroids may have been crystallized, that does not imply that there cannot have been interstices between their minerals, as long as there were small quantities of magma still circulating between them. There are many facts observed both here and in other rocks that point in the same direction, making it conceivable that there has existed an intermediate state between the time of the crystallization of the main part of the constituents and the ultimate consolidation of the last residual portions of the magma.

Frosterus, too, admits that a part of the feldspar had been solid before the crystallization of the main portion, which, as he thinks, took place later than that of the biotite crystals. His assumption that most of the biotite crystals were evenly distributed in the mass in process of crystallization, and were conveyed to the spheroids by convection currents during the crystallization of the main part of the feldspar, is, however, hardly compatible with the idea that the biotitic layers should have existed alone, without alternating feldspathic layers, already before the deformation occurred.

THE CEMENT.

The cement between the spheroids also presents, in the granite of Virvik, some points of very great interest. In the first place, as follows from Frosterus' analyses, it is richer in potash than in most other orbicular rocks, and the chemical difference between the spheroids, in which oligoclase prevails, and the cement is consequently greater than usual. They also show clear evidence of fluidal movements that have occurred in the portions between the spheroids and caused the formation of »Schlieren». In some cases even veins or vein-like stripes of pegmatitic material are visible, making it probable that an influx of new material has taken place.

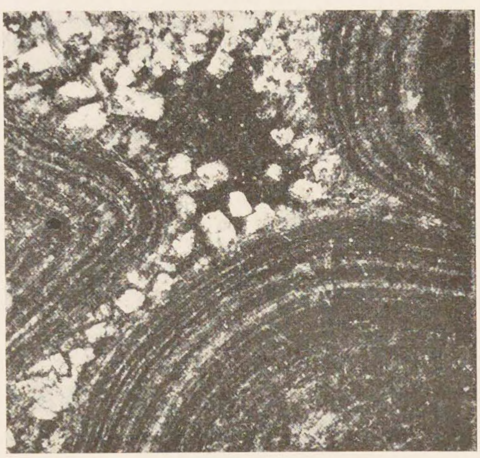


Fig. 11. Cement between spheroids differentiated in femic and sialic portions. Virvik, Borgå. 1/2 nat. size.

Most of the differences in the composition of the cement are, however, due to differentiation processes which have been caused by a fractional crystallization. This is particularly clear in the case shown by fig. 1,

plate IX. By the crystallization of the cement, feldspar has first been formed, coating the walls of the interstices between the spheroids. The residuum has become more and more enriched in biotitic material which has later crystallized, filling the middle of the interstice. The same phenomenon is very evident at several other places, e. g., in the slab shown by fig. 11. Here, too, the feldspar coats the walls of the interstices between the spheroids, and seems to have had its crystallization directed inwards, while the last residuum has been very rich in biotite. It is a most typical case of fractional crystallization. These observations are entirely in harmony with those which have been made on the other orbicular granites.

THE ORBICULAR DIORITE FROM PÖYTYÄ IN S.W. FINLAND DESCRIBED BY PENTTI ESKOLA.

A very interesting orbicular rock was found in 1917 in Pöytyä in S. W. Finland.

As it deserves to be better known, the description given of it by Professor Pentti Eskola is here reproduced, in translation from the Swedish record of the meeting of the Geological Society of Helsingfors on the 13:th December 1917. This record is an authorized translation from the lecture which was given in Finnish.

Mr P. Eskola spoke about a newly discovered orbicular diorite from Pöytyä (= Pöytis) in S. W. Finland. A boulder, of the size of about a cubic metre, was found in the neighbourhood of the village of Riihikoski in the parish mentioned. The composition of rock adjacent to that of the boulder is thus not known. The rock masses of the region consist of striped gneissose granodiorites and diorites, and W. of the place where the boulder was found, migmatites outcrop, composed of mica gneiss and migmatitic granites. The rock in question (fig. 12) is composed of light spheroids which have at the same time a concentric and radial structure and measure on an average 7 cm in diameter, and lie densely crowded in a dioritic matrix which is coarsely equigranular. The spheroids possess somewhat irregular forms, obviously because they have been squeezed against each other at a time, when the matrix was still fluid. All spheroids, however, are unbroken and show no traces of resorption phenomena. The inner structure is also very regular both in the matrix and the spheroids. In the innermost part of the spheroids are some single individuals of dark-green hornblende. Otherwise, the central portion consists of coarse laths of andesine (with an angle of extinction in sections perpendicular to P M of about 20°) which are radially arranged and drawn out parallel to the zone P M. This

central portion measures about 6 cm in diameter, but a marginal zone of it which is about 1 cm broad contains, besides andesine, numerous small grains of m a g n e t i t e. About 0.5 cm from the margin of the zone a dark ring is always visible in which the magnetite grains are almost in contact with each other. At the outer side the spheroid is surrounded by a shell, 0.5 cm thick, which consists of a fine-grained

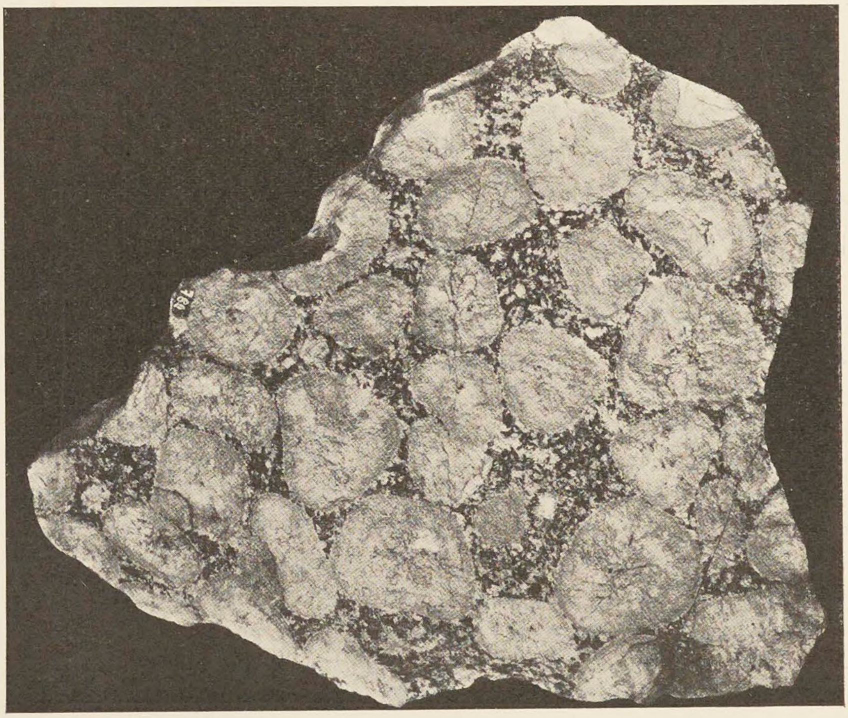


Fig. 12. Orbicular diorite from Pöytyä. Specimen taken by Pentti Eskola. 1/3 nat. size.

mass of andesine with disseminated grains of magnetite that give it a somewhat darker colour than the inner portions. The matrix between the spheroids consists of andesine and dark green hornblende in about equal proportions and is then absolutely similar to the non-gneissose varieties of the quartz-free diorites of the region. It is noteworthy that the composition of the plagioclase seems to be the same in the matrix and in the spheroids. Potash feldspar was not observed, and quartz only in small quantities in the inner parts of the spheroids. The rock has no secondary minerals, nor other accessory constituents than magnetite and some apatite.

The speaker knows no instances of orbicular rocks directly comparable to this orbicular diorite. The felsic composition of the spheroids and the beautiful equigranular dioritic structure of the matrix seem to be very peculiar features. It is true that it is common to this and several other cases, e. g. the variety with small spheroids of the orbicular granite from Virvik, that the inner portions of the spheroids mainly consist of plagioclase. There is nothing in the orbicular diorite from Pöytyä to suggest that the crystallization originated around fragments of foreign rocks. It looks as if centres of spontaneous crystallization had been formed, around which the anchi-monomineralic spheroids were formed, till the residual magma received an anchi-eutectic composition and finally consolidated as a dioritic mass. Through such an explanation the rock in question would provide an almost ideal case of the formation of an orbicular rock.

The following members took part in the discussion: W. Ramsay, J. J. Sederholm, W. Wahl, L. H. Borgström, V. Hackman, A. Laitakari, Th. Brenner and the lecturer.

Mr. Ramsay thought that Benedicks' explanation, according to which the spheroids were recrystallized fragments, was the most plausible.

Mr. Sederholm emphasized the importance of viscosity as conditioning the orbicular structure. He further thought it possible that the hornblende in the interior of the spheroids could have crystallized later than the feldspar.

Mr. Borgström compared the spheroids to spherulitic structures and to chondres which latter are drop structures.

THEORETICAL CONCLUSIONS CONCERNING THE ORIGIN OF ORBICULAR GRANITES.

While trying to explain the origin of the orbicular structures, the author will also make a summary of the earlier theories, reviewing them critically.

ARE THE SPHEROIDS CONCRETIONS?

The first question which presented itself to many inquirers is, whether the spheroids are formed by c o n c r e s c e n c e or, on the contrary, by a crystallization which has started from the periphery and proceeded towards the centre. Structures of the first kind may be called c o n c r e t i o n s, c o n c e n t r i c or perhaps better p e r i c e n t r i c structures, i. e. such as have originated around a centre. Popoff calls them c e n t r o g e n e (65), but this expression

is not quite adequate, because it would mean formed at, or in, a centre. Structures of the second group, if they exist, may be described as having been formed by a centripetal or eisotropic (inward turned) crystallization, while the pericentric structures are centrifugal or exotropic. The reason why the author prefers the Greek designations is that the Latin ones also awake other ideas than those which we are concerned with here.

Refutation of the liquation hypothesis. Bäckström has advanced a hypothesis according to which the spheroids, at least in some of the orbicular rocks, may really be eisotropic (12—15). The first stage may be the formation by liquation of drops of magma with a composition differing from that of the surrounding magma, and in them the crystallization may have proceeded from the margins towards the centre. The reasons which brought Bäckström to this idea were partly a theoretical conception in which he followed Durocher, concerning the importance of liquation for the differentiation of magmas (12), and partly a belief in the validity of Rosenbusch's so-called »law of decreasing basicity» in the sequence of the minerals of a crystallizing magma. As the outer shells of the spheroids of some orbicular rocks were more basic (or rather femic), while the inner were preponderantly sialic, Bäckström thought it impossible to assume that the former were later.

However, the regularity in the sequence of the minerals crystallizing in a granitic magma is by no means as great as Rosenbusch thought. In the granites of Finland, the biotite has more often crystallized later than the feldspars than the reverse. Thus the alleged »law» cannot be made the basis of such far reaching conclusions as those drawn by Bäckström.

Most of the observations made by the present study point in an opposite direction. Very little evidence has been found in favour of a liquation and none of one possessing the character admitted by Bäckström, leading to the formation of magma drops. His ideas have, however, played a considerable rôle through the discussion of the differentiation phenomena and especially also of the orbicular granites. Daly shares Bäckström's opinion, thinking that »probably all orbicular granites, diorites and gabbros are direct evidences of the emulsion stage» which is a consequence of the limited miscibility of the molten magmas (21). Högbom, Holmquist, H. E. Johansson, Asklund and other Swedish petrologists have also followed Bäcktsröm in using the liquation hypothesis for explaining the differentiation processes, and, in general, a number of phenomena occurring through the crystallization of deep-seated rocks.

As to the fundamental conceptions underlying the liquation theory applied to petrological phenomena, it has now been proved, by the researches of Greig (33), that silicatic melts exist which are not miscible, but of which parts separate as drops in the same way as oil from water. The composition of these melts, however, lies outside that of common eruptive magmas. As to these, it seems, on the contrary, to be proved, or at least exceedingly probable, that they are able to mix in all proportions. This fact does not prevent the possibility of there being a limited immiscibility under certain conditions, as shown by the existence of Schlieren, e. g., in the groundmass of effusive rocks.

It is, however, less from a theoretical standpoint that the present author objects to the application of the liquation hypothesis for the explanation of orbicular rocks, than because he thinks that it is at variance with observed facts.

First, it is very difficult to account for the repeated alternation of sialic and femic shells by assuming that the magma has split up by liquation into drops of different composition. Bäckström had observed analogous phenomena, which he explains by a repeated differentiation, by liquation, but none of those which he describes are very typical. If we try to apply his explanation, e. g., to spheroids of the Kangasala rock, with their twenty times repeated alternation of shells of sharply differing composition, we should be obliged to assume the existence of drops of magma of so strange a »bulbous» structure that it leads to a reductio ad absurdum of the whole theory.

Moreover, there are, as we have found, cases (Esbo), where the difference in the chemical composition of the spheroids and the cementing mass is nil, or at least very inconsiderable. In this case, obviously, no individualized drops have been able to exist.

The structure of some of the nuclei of the Kangasala rock, e. g. those which are composite, is such as to indicate strongly that they are older than the next surrounding shell of the spheroids. The nuclei consisting of fragments of foreign rocks must, of course, also be older than the main parts of the surrounding spheroids.

There are varieties of some orbicular granites (Virvik, Esbo, etc.), where the minerals or mineral aggregates which form the nuclei of the bigger spheroids, occur also alone, surrounded by no shell or by such as possess a very simple structure. It is impossible to imagine that these aggregations should have acquired quite the same character when they form the nuclei of a spheroid, as when they have originated per se in the magma, if they were the last crystallization residua

of the latter. The Virvik rock shows an instance, where the rock containing small spheroids was taken up, at an early epoch, when they were however, c r y s t a l l i z e d bodies and not magma drops, by the magma of a granite dyke where it was partly refused and the spheroids became scattered before the granite was again finally consolidated (fig 1, plate VIII). Both in the Virvik and the Esbo granite, we also observe small spheroids lying between the big ones.

The r a d i a l a r r a n g e m e n t of the feldspar crystals, in a way reminding one of microspherulitic structures, is another reason for assuming a crystallization from within outwards. The arrangement and composition of the alternating femic and sialic shells, too, e. g. in the Kangasala rock, is such as only to allow of an explanation by a successive deposition around an inner nucleus. This is specially striking, when the biotitic layers are lying unconformably on the ends of the plagioclase crystals (cf. fig. 3, plate XV).

THE SPHEROIDS ARE EXOTROPIC STRUCTURES.

The spheroids have been formed through the deposition of minerals, layer upon layer, around the central nuclei. Thus every outer lying shell is later than the next inner lying neighbour.

The most d e f i n i t e p r o o f of the exotropic character of the crystallization process by which the spheroids have originated, is the fact observed in the Virvik granite, that the outermost layers of alternating mica and feldspar have been deposited u n c o n f o r m a b l y upon the inner shells, after an epoch when these were partly eroded. This fact is absolutely at variance with the assumption of an eisotropic structure.

ONE EXCEPTION TO THE GENERAL RULE.

One exception, however, exists to this general rule. In the spheroids which possess a central nucleus of a foreign rock, the composition of which is very different from that of the orbicular rock itself, there may be formed, through its progressive assimilation by the magma still circulating in the spheroid, next to the fragment a magma zone which has, according to the observations of Frosterus (29) and Cole (19), even been able to penetrate, in an eruptive way, the surrounding outer shell, forming veins in it which join with the still fluid magma that surrounds the spheroids. It is evident that this inner zone of magma may then be able also to react upon the adjacent parts of the enveloping shell which have therefore partly been replaced by a granite-like rock. The »stratified» shells have, in this case, not been deposited on the next inward lying shells in their pre-

sent composition, but on earlier existing shells which have later been changed by a kind of autopalingenesis. In any case, we must not let this exception to the general rule detract from the value of the clear evidence gained in so many other ways about the pericentric character of the spheroids.

The above explanation presupposes that the magma is really able to circulate between the minerals of the surrounding shells. This will be made clear later. That the magma really continually reacts upon the metabasitic fragments, is shown by the figures and the explanation given above. It is difficult to imagine, how the phenomena shown, e. g., in the photographs of microscopical sections of the Kangasala granite, could be explained from the standpoint of the liquation theory or, in general, by any other assumption than that the spheroids have grown from within outwards.

ALL SPHEROIDS HAVE BEEN FORMED AROUND A NUCLEUS.

As was stated already by von Chrustschoff and Frosterus, and as the present writer has found by studying a great many different orbicular rocks, the spheroids always contain a central nucleus which has existed before the formation of the outer shells. This nucleus may be either 1:o a crystal, 2:o a group of crystals, formed at an early epoch, 3:o several groups of crystals (composite nuclei), 4:o fragments of a rock, similar to the surrounding one, or 5:o fragments (xenoliths) of rocks of different character. There are gradations between all these groups. Thus, e. g., xenoliths seem in some cases to have existed which have later been gradually replaced by minerals similar to those of the rock surrounding the spheroids, and then these nuclei may resemble those of the groups 2—4.

Popoff's criterion. Popoff has proposed to discriminate between different kinds of spherulites, or, between structures which have been here called eisotropic and exotropic, by observing, if they have suffered any influence preventing their growth on the part of their neighbours (64, 65).

Such interference can, however, only occur, if the obstacle has a stable position. If, again, both bodies are freely swimming, there can be no visible interference of this character. Thus this criterion seems in many cases to be rather difficult to apply. In the present case it is also unnecessary, because there are so many other proofs of the exotropic way of crystallization. Popoff has shown instances, where spherulites lying in the groundmass of a porphyrite from Corsica have really suffered such an obstruction to their growth. In this case it is probable that the surrounding portions of the rock, which

was then in the last period of its solidification, was already fairly stiff. As to the orbicular granites, interference by neighbouring spheroids has, no doubt, occurred, but they seem to be due to lesions caused by freely movable bodies, and not caused by an obstruction to the growth of any of the spheroids by its neighbour.

THE SPHEROIDS ARE FORMED BY THE CRYSTALLIZATION OF A MOLTEN MAGMA.

Hess has suggested that the spheroids of orbicular rocks may have grown at the expense of their neighbours' space and in part possibly at the expense of their substance (39). In the rocks here studied no evidence has been found showing that such a process may have played any rôle. It is true that some spheroids have been partly destroyed by magmatic resorption, after having been split, but these changes have not taken place in such a way that it could be said that the spheroids have been formed at the expense of their neighbours. In general, we have found that the orbicular granites are formed by the primary crystallization of a molten granitic magma. The resorption, autopalingenesis etc. are, in this particular case, subordinate processes, not necessary for the formation of these structures. These remarks do not imply that here, as well as in many other rocks, a refusion of certain minerals formed in the magma, especially in the initial stages of its solidification, could not have occurred.

DISTRIBUTION, NUMBER AND SIZES OF THE SPHEROIDS. RELATIVE QUANTITIES OF SPHEROIDS AND CEMENT.

We now approach the difficult problem as to why only a limited number of centres of crystallization has been formed around which the minerals have gathered, and not as usual in eruptive rocks, a great number of smaller crystals have originated independently of each other.

In the varieties of the Virvik and Esbo rocks containing small spheroids, these lie crowded, and the matrix is not more abundant here than in the variety with big spheroids in which the minerals forming the small spheroids of the former variety have been later surrounded by thick shells of plagioclase and biotite. Either the nuclei have originally lain more dispersed in the latter case, or else a gradual influx of magma has occurred, so that material for the continued growth of the spheroids was always available.

As movements seem to have taken place dividing the rock masses, especially in the space between the spheroids, it seems possible that they may have facilitated the influx of magma. We can also

imagine that the spheroids were slowly sinking downward from the surface, where their formation first began, or rising, and spread during any of these movements.

In the Virvik rock, there seems really to be evidence of an influx of magma which has a somewhat different composition from the rest of the rock.

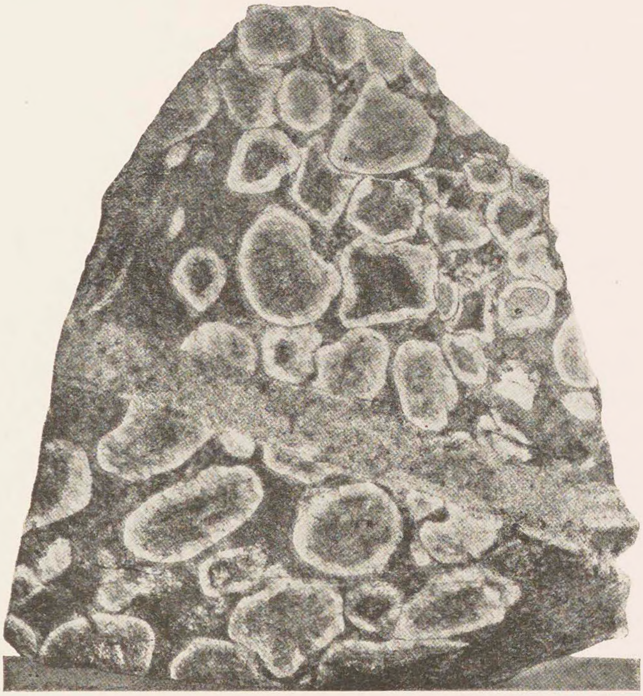


Fig. 13. Orbicular granite from Stockholm. Specimen in the Museum of the Geological Survey of Sweden. C:a 1/10 nat. size.

In no other orbicular granite is there so much evidence in favour of a magma which was still continually flowing, during and after the consolidation of the spheroids, as in the Stockholm granite (8, 32, 43). A magnificent specimen of this granite, exhibited in the museum of the Geological Survey of Sweden, is here reproduced with the aid of a stereotype, kindly lent by Director A. Gavelin (fig. 13). This photograph gives the impression that the whole mass has been moving at an epoch when the spheroids had not yet entirely solidified, but also that veinlike stripes have been formed during the crystallization of the matrix, possessing no very sharp delimitation towards its main portions, while other sharply cutting granitic veins have been formed after the complete crystallization of the orbicular rock.

If there had been no influx of magma, and no spreading of the spheroids during their growth, we should be forced to conclude that the bigger spheroids originated, because there was ampler room available for their growth, in other words that the nuclei would have been originally sparser here than in those portions where the rock with small spheroids originated. The existence of single small spheroids between the bigger ones shows, however, that spheroids could originate in the magma also at a late stage of its crystallization. In any case, it seems probable that the crystallization of all spheroids did not begin simultaneously in all centres.

The varying sizes of the spheroids seem to indicate, that these grew either as long as there was any material available around them, or until the causes conditioning the orbicular structure ceased to exist.

In some cases, the different spheroids seem to have passed through the same, or similar stages of development simultaneously in all the rock mass, in other cases, again, they show great individual differences.

The ratio between the mass of the spheroids and the matrix has been determined by measuring their areas exactly in photographs of rock surfaces, on polished slabs or on the outcrops. The folloving list gives the result. In most cases, the spheroids form 60—70 per cent of the whole rock. Only in the small slab of Puutsaari granite, the area of the spheroids was found to be less.

Volume of spheroids in per cent of the whole rock mass.

Puutsaari	52
Esbo	58—60
Kangasala, variety with smaller spheroids	60
Pöytyä	60
Virvik, variety with bigger spheroids	61—68
» » » smaller »	62
Hankasalmi	66
Kangasniemi	70

The maximum size of the spheroids seems to be something like 30 cm.

The question as to the relative number of the centres of crystallization is a part of the general problem which we meet in all endeavours to explain those variations of the grain of igneous rocks which are caused mainly by the size of the minerals, viz. the porphyritic and granular textures and the like. As the formation, in orbicular rocks, of concretions around a very small number of centres of crystallization, is an extreme case, we may hope to be able to throw light

on that difficult problem, and in general, the conditions of the crystallization of deep-seated magmas, by the present studies.

On the other hand, it is necessary to discuss the formation of granitic textures in general, before we can attack the special problem which is here discussed. A digression from the general trend of reasoning is here unavoidable.

ORIGIN OF THE PORPHYRITIC AND GRANULAR TEXTURES IN ERUPTIVE ROCKS.

The most conspicuous difference in the grain of igneous rocks is that between porphyritic and equigranular rocks, and therefore the discussion of the origin of the porphyritic texture has played a prominent part in all endeavours to explain the crystallization of a molten magma.

The explanation offered by Rosenbusch, according to which the porphyritic crystals are probably always i n t r a t e l l u r i c, (72), while the groundmass probably crystallized after the arrival of the magma at the surface or at higher levels, where it cooled more rapidly, may be applicable in some cases, but fails to account for a number of phenomena observed in rocks which have solidified under the surface.

Later, when so much new light was shed on petrological chemistry by the study of eutectics, an attempt was made to explain the porphyritic texture, too, as being due to a tendency of the rock magmas to approach a e u t e c t i c composition. The phenocrysts would represent the excess over eutectic proportions, the groundmass the eutectic or anchi-eutectic residuum. Theories in this sense have been propounded by Becker (2), Vogt (88—90) and others, especially as to the origin of the groundmass of acid rocks.

The present writer has never been able to find that the igneous rocks have quite as great a predilection for eutectic proportions as many petrologists have. Experiments and a vast array of observations show that the magmas are freely miscible in almost any proportions. There seems to be a continous series, connected by gradual transitional stages, between the most acid granites, on the one hand, and gabbros and peridotites, on the other, and also between the rocks mentioned and alkaline rocks.

This refers not only to the bulk composition of the igneous rocks themselves, but also to their groundmasses.

In the common rocks, often no marked difference in composition exists between phenocrysts and groundmass. In most of them, especially also in granites, we find the same minerals as phenocrysts

and as components of the groundmass. Vogt thinks that there is a tendency of the groundmass of different rocks to approximate to the composition of a feldspar-quartz eutectic, such as a graphic granite, but as Harker admits (35), this approximation is, in any case, only of a rough kind.

As to the rapakivi granites, which are often quoted as offering evidence in favour of these ideas, it seems more than doubtful, whether there is any such approximation. The minerals first crystallized are commonly feldspar and quartz, while the biotite and hornblende have, in many varieties, consolidated later, and may be constituents of the ground-mass. It seems certain that this is, in many cases, more removed in composition from a eutectic proportion than the magma before the beginning of the crystallization.

These statements can be easily proved by a detailed study of the rapakivi rocks, in which the biotite, contrary to the opinion of the Rosenbusch school, is in general a mineral of later origin than much of the feldspar and quartz.

In a porphyritic rock composed of plagioclase, augite, olivine and ore, we usually find these minerals, except the ore, both as phenocrysts and in the groundmass. Such examples could easily be multiplied, showing that this chemical theory entirely fails to explain the porphyritic texture.

Miers has advanced another theory of the porphyritic texture, explaining the phenocrysts as the result of i n o c u l a t i o n in a magma which has reached metastable conditions (59). Harker has objected that inoculation must be an exceptional thing in rock magmas (35). Although the present author believes that assimilation of foreign rocks occurs on the most extensive scale in many granites, he cannot, however, think that it is so universal as to allow us to account for the origin of porphyritic crystals solely by inoculation. For instance, the rapakivi granites are fairly free from inclusions, and yet we here find a porphyritic texture, and other related textures, uniformly spread over wide areas.

If, therefore, none of these theories covers the phenomena observed, we must look for another explanation of the porphyritic texture in igneous rocks.

Pirsson has, probably earlier than anybody else, laid stress on the importance of variations in the viscosity, especially by the formation of the groundmass (63).

»Another important consideration», he remarks, »which has been greatly overlooked, is increasing viscosity which depends on chemical composition and temperature: The viscosity depends greatly on the

included water vapour». »If this is present in large amount, the fluidity of the magma is enormously increased, and with it the radius of action of each crystallizing center, that is, the crystal, has a free chance to grow, orient material and expand». »On the other hand, absence or scarcity of water causes an increase of viscosity, the radius of action of each center is small and, although the crystallization interval may be sufficiently long, the crystals are restrained in their growth, new centers are set up and the rock is finegrained». In the basic rocks, Pirsson thinks, the water vapour has no such function.

Pirsson, therefore, explains the formation of some porphyritic textures in an acid magma by the increase of viscosity. It means shorter and shorter crystallization intervals for the various components as their periods commence. Thus the earlier ferro-magnesian components may have time to grow to a considerable size, while the increasing viscosity forces the feldspars and later components to be of very small size. Thus we may have a porphyritic texture with phenocrysts of the monogenetic type as a result of a single process of crystallization.

The latter theory, which starts from the idea of Rosenbusch that the femic minerals always crystallized earlier, seems to the present writer not to have a very wide bearing on the phenomena actually observed. But Pirsson gives another explanation also for the phenocrysts of the recurrent type. He believes that the influence of mass action is of great importance and that compounds which are present in relatively large or predominant quantity tend to set up centres of crystallization before what might otherwise be the proper period for that component. »The rest of the process might go on as noted above, and a porphyritic structure would be formed with phenocrysts of the recurrent type».

Other petrological writers too, have propounded similar opinions.

Thus, Hatch and Wells (37), while in the main accepting Rosenbusch's explanation of the porphyritic texture, point out, in their Text-book of Petrology, that the formation of the phenocrysts was started under the influence of slow cooling, when widely-spaced centres of crystallizations originated and free molecular diffusion existed. A sudden change to a condition of increased viscosity checked the supply of fresh material to the growing phenocrysts, and induced the setting up of many new centres, with consequent rapid consolidation of the liquid portion of the magma of a groundmass.

This abrupt change, they think, is consequent upon an increased rate of cooling, caused either by effusion or a transference from deep-seated to superficial portions of the earth's crust.

The present writer thinks, like Pirsson, that viscosity is of paramount importance in determining the texture of igneous rocks, as far as it is determined by the size of the minerals. Not only in acid, but also in basic rocks, where the increasing viscosity is caused more by the fall of temperature, than by the escape of water vapour, viscosity may be the chief determinant for the porphyritic texture. The variation of the viscosity is in general dependent on complex causes, among them also the composition of the silicatic magma. This question will be discussed further below.

By eliminating such theories as seem inadequate, we arrive at the following conception of the origin of the porphyritic texture, and other textures depending mainly on the different size of the silicatic minerals.

When a cooling magma has reached metastable condition, there is, if no occulation occurs, probably a stage, at which a very great number of centres of crystallization are formed. But among these minute crystals a struggle for life at once begins, by which some of them are handicapped. Around every crystal in being an aureole is formed next to the crystal: a zone of diluted solution exists to which material is transported by diffusion. The different spheres of diffusion, each with a crystal in its centre, compete with each other till they have grown bigger and the magma is divided into a certain number of »tributary regions», each belonging to a different crystal, all constantly as desirous of conquest as any warlike community of human beings.

The more fluid the magma, the greater are, c e t e r i s p a r i b u s, these tributary regions surrounding each crystal.

Between these tributary regions there may be spaces in which a magma with different composition begins to gather, but if the magma is fluid enough, the inequalities will in general be obliterated by diffusion.

By a slow cooling accompanied by a removal of water, this process may continue almost to the end of the crystallization, although the increasing relative amount of mineralizers, movements during the final stages of solidification, etc., may cause modifications of the regular granular texture.

If the cooling progresses rapidly, the magma reaches, independently of its being stationary or in motion, a stage, at which the diffusion is very much hampered by growing viscosity. The bigger crystals lose there tributary regions, and a great many new centres of crystallization are formed, which, however, are doomed to be the rulers of very small empires. A ground-mass of smaller crystals is formed.

Only in effusive rocks, or in small dykes near the surface, the cooling and the escape of water are so rapid that diffusion becomes practically n i l, and the mass solidifies as a glass.

For the formation of a vitrophyric rock, it is by no means necessary that the magma should be in motion during the crystallization, but only that it should be rapidly cooled. The rock of a dyke whose middle is equigranular, while the border zones are porphyritic, and the contacts glassy, may have originated by the solidification i n s i t u of one simultaneously erupted mass of magma, whose different parts have cooled at different rates.

In the groundmass of a rapidly crystallized porphyritic rock of granitic composition, s p h e r u l i t i c structures are formed, although of minute size. It is the last endeavour of certain minerals to attain greater importance, not by subjugating, by means of diffusion, a larger region of surrounding magma, as this is prevented by the increased viscosity, but by directly continuing their rapid growth outwards as long as any material is available. The spherulites are centric structures which, without any doubt, have crystallized exotropically. They sometimes contain a minute crystal of feldspar as a centre, and in that case the analogy to some of the spheroids with similar structure is pretty close.

In some cases, water or gases may have accumulated in vesicles, in which crystallization processes occur later.

Phenomena exist which seem, at the first glance, to be at variance with the above conceptions. In porphyritic granites, fragments are observed which contain porphyritic crystals that have quite the same character as those of the surrounding granite. Thus we sometimes observe, in the rapakivi fragments of foreign rocks which contain rounded orthoclase crystals that show the usual rim of oligoclase. Within the borders of the fragments, we might think, the conditions of liquidity ought to have been very different from those in the surrounding magma. However, if we admit that the fragments became thoroughly permeated with magma, or magmatic ichor, during the long continued process of the formation of the feldspar ovoids, it is by no means impossible that the diffusion processes may have taken place almost as freely within the fragments as in the magma around them.

DIFFERENCE BETWEEN THE CRYSTALLIZATION OF A CRYSTAL AND A SPHEROID.

By an endeavour to apply the above conceptions to the orbicular structures, it becomes at once evident that there is no close analogy between the growth of a porphyritic crystal and the growth of a spher-

oid. It is true that both are formed by an afflux of material in solution. But, as shown by their uniform composition, porphyritic crystals are surrounded by a zone of magma whose composition long remains very little changed, because diffusion obliterates, in most cases, the difference between the depleted region next to the crystal, and the magma farther from it. The spheroids, again, have a very heterogeneous composition, and there has obviously often been a marked rhythm in the deposition of sialic and femic layers. This seems to show that the composition of the magma next to the spheroid in formation has continually changed. The reason must be that the diffusion has been hampered, so that material could not be rapidly conveyed from greater distances.

THE CAUSE OF THE DISPERSEDNESS OF THE CENTRES.

As has already been explained, the dispersedness of the centres of the small spheroids may be, in some cases, explained in the same way as that of the minerals of granites with a similar grain. As to the bigger spheroids, again, they may have spread during their formation either through sinking movements or through the influx of new magma between them.

Lawson, while assuming that the differentiation has been rhythmically recurrent, thinks that the approximately uniform spacing of the centres of the spheroids may indicate the special limits of osmotic currents within the time necessary for crystallization (51). This explanation is easily applicable to crystals forming the centres, if they exist, but as to the formation of the spheroids, it presents greater, although perhaps not insuperable difficulties, because diffusion has probably, in the present case, not been easier, but, on the contrary, much more difficult than in the crystallization of most even-grained rocks.

It is, in any case, not necessary to suppose that the crystals which form the centres of certain spheroids were the only crystals that were formed at the earliest stage of the consolidation of the rock in question. There may have been, at the outset, a greater number of minute crystals which either were remains of dissolved fragments or crystallized as numerous slender needles, when the metastable condition had been transgressed. So many radical changes seem to have taken place at different epochs in the composition of the magma, causing a casual heterogeneity, that these minute crystals have easily been destroyed by resorption. In other cases, they may have been taken up by other bigger crystals, or aggregates of the latter. The crystallographical orientation was then either from the beginning parallel,

or became so by recrystallization. Thus, the first period of the crystallization of the magma may have been fairly similar to that of other deep-seated rocks. It was mainly at the formation of the shells of the spheroids that peculiar conditions of crystallization prevailed.

IMPORTANCE OF FRAGMENTS OF FOREIGN ROCKS AS CENTRES.

Benedicks and Tenow go farther than anybody else in emphasizing the importance of fragments of foreign rocks as centres (3). They not only think that such are necessary for the formation of orbicular rocks, but that the spheroids simply a r e refused fragments, in which a differentiation has taken place, when they were melted. They quote instances in which the fragments in the Uppsala granite show an indistinct concentric structure, and have also made experiments with paraffin by which they have observed phenomena which have some likeness to spheroids. This similarity is, however, in both cases rather vague. The study of the fragments occurring in connection with the orbicular granite of Esbo shows that there is a distinct difference between fragments with marginal zones, formed by refusion, and the true spheroids. In the Archæan of Finland and Sweden, eruptive breccias occur over very wide areas and often well exposed. Among the millions of fragments which may be observed in them, none have been found anywhere which really have been directly changed into spheroids. When concentric shells have been formed around fragments, other causes than refusion have always been concomitant.

In any case, it cannot be denied that fragments of foreign rocks have often played a considerable rôle as centres. This is most obvious in regard to the Kangasniemi and Mullaghderg rocks, but also in the Esbo and Kangasala rocks we occasionally find fragments at the centres, and in the former it seems certain that more existed in an earlier stage, but were destroyed later by magmatic assimilation.

In the Puutsaari, and still more obviously, in the Stockholm granites, the centres, again, consist of fragments of the same eruptive rocks to which the orbicular rock belongs. Fragments of protoclastic breccias have been surrounded later by shells rich in plagioclase.

As to the orbicular granites with big spheroids, it seems, therefore, fairly probable that in a great many cases the crystallization began around centres of preexisting rocks. One might be tempted to generalize these conclusions, and to assume that the orbicular granites with small spheroids may also have originated by the brecciation of a rock mass, either after its complete solidification, or at a late stage of it. The rock may thus have been divided into a num-

ber of small fragments, around which other minerals gathered later. However, it is difficult to understand how they could in this way have become so uniform in size as they are, e. g., in the variety with small spheroids of the Virvik granite.

Moreover, there is one fact which seems absolutely at variance with the idea that the small spheroids were always fragments of older rocks or earlier consolidated portions of the same rock. This is the occurrence of small spheroids within the borders of a fragment of migmatite in the orbicular granite of Esbo (fig. 2, plate III). In this case, they cannot have been formed by brecciation of a granitoid rock mass, but must have originated in situ, in the same way as the porphyritic feldspars which have crystallized within the borders of a fragment lying in an eruptive rock.

As already mentioned, the formation of small spheroids in rocks like Virvik or Esbo seems to have most affinity to the formation of porphyritic constituents in deep-seated rocks. In some cases, e. g., in the Hankasalmi and the Virvik rock, a part of the nuclei are really crystals of feldspar or biotite, although not very perfect in shape nor quite homogeneous in their crystallographical orientation. In the Sardinian granite from Ghistorrai near Fonni, feldspars which form Baveno twins have also been observed as centres of the spheroids (18, 27, 54).

IS A DIFFUSION IN RADIAL DIRECTIONS NECESSARY FOR THE FORMATION OF SPHEROIDS?

Von Chrustschoff thought that the formation of orbicular structures was favoured by the occurence of crowded fragments (18). This condition caused corrosion and resorption to be started, a renewed crystallization of minerals took place, mixed zones were formed and, in consequence, there followed a crystallization which was radially arranged.

Frosterus adheres to von Chrustschoff's explanation, but he thinks that in certain cases, where greater phenocrysts have served as centres of crystallization, the surrounding magma may have been rich in products of magmatic differentiation which have, in a certain sense, been analogous to the resorbed portions of a fragment (28, 29).

As Frosterus has, however, himself shown that the nucleus may be a feldspar crystal or a group of them which cannot have played the same rôle as a fragment of basic composition, the shells lying next to these feldspar nuclei must have gathered for some other cause than conventional currents caused by the dissolution of the central portions.

Otherwise, von Chrustschoff and Frosterus, as well as Cole, who also adopted the same explanation, were nearer the truth than most other petrologists who have written on that subject, because they have emphasized the importance of the existence of nuclei, in many cases consisting of fragments, and also of a hybrid character of the magma.

THE RÔLE OF EUTECTICS.

Vogt regards the orbicular granites as a typical case of a crystallization regulated by a eutectic composition of the magma. He quotes Frosterus' analyses of some of the shells in the Virvik rocks which possess, according to Vogt, a composition nearly corresponding to the eutectic mixture of quartz and orthoclase (89—91). However, the composition quoted is by no means characteristic of that of the shells of spheroids in general, but, on the contrary, very exceptional. Usually the shells consist of oligoclase mixed up with microcline, biotite and quartz in very varying proportions. It is therefore impossible to suppose that all of them represent a eutectic composition. While not denying that the eutectic proportions may have played a part in some instances, the present author is unable to find that they could account for the orbicular structures. Especially if they were as common in different magmas as Vogt believes, it is impossible to understand, why the orbicular structures should be so rare, if they were due to eutectics. We will return to that question later on.

Lawson, too, explains the marked rhythm in the formation of the minerals of the orbicular gabbro from Dehesa in California studied by him (51), as due to eutectic phenomena, but also to repeated changes of temperature, caused by the liberation of heat during the crystallization. He further assumes that diffusional currents in radial directions have orientated the minerals.

WIIK'S HYPOTHESIS.

Among older explanations of the orbicular granites there is still to be mentioned Wiik's hypothesis, according to which the spheroids became coated with coverings of different composition, when passing through layers of magma with varying composition (95). We will discuss a similar explanation of the origin of the orthoclases coated with oligoclase of the rapakivi later on.

THE IMPORTANCE OF DIFFUSION AND VISCOSITY AS CAUSES OF THE RHYTHM IN THE DEPOSITION OF THE ALTERNATING SHELLS.

In the structure of the spheroids two phenomena, which are to a certain extent independent of each other in character, may be discerned. One is the r a d i a l arrangement of some of the constituents, especially the feldspars. The other is the c o n c e n t r i c arrangement, especially of the femic components. In some cases, these phenomena are so independent of each other that the different components could be compared to the warp and weft of a web, in others, again, they are less clearly separated.

It is especially the arrangement of the dark shells marked by biotite, in some orbicular granites also by hornblende, magnetite, etc., that causes the concentric structure which is suggestive of a rhythm in the crystallization process.

Several of the writers quoted have already offered suggestions pointing in the direction in which the present author thinks that the true explanation lies.

Liesegang has, in his sagacious work on geological diffusion phenomena (52), expressed the opinion that the formation of spheroidal structures in magmatic rocks, as, e. g., those observed in orbicular diorites, are analogous to the rhythmical precipitations which he assumes to be the cause of the origin of certain concretions in sedimentary rocks. Erdmannsdörffer also says, referring to Liesegang, that the phenomena visible in orbicular diorites, norites, etc., are in many cases to be regarded as rhythmical, pulsatory processes of supersaturation and crystallization (24). Liesegang's experiments on diffusion have had the purpose of explaining a great many different geological phenomena, such as the banding of the achate nodules, the peculiar zonal structures of ore tubes described by Trüstedt from Pitkäranta in Finland, and a great number of different globular structures.

Most of these experiments refer to cases, in which rhythmical p r e c i p i t a t i o n has taken place, e. g., when silver chromate is rhythmically precipitated in gelatine, by the interreaction of potassium bichromate contained in it, and a drop of silver nitrate placed upon it. The latter spreads centrifugally, and rings of silver chromate are formed around it whose distances gradually narrow with increasing distance from the central drop, or, in other words, in proportion to the dissolution of the diffunding solution of silver nitrate. The explanation of the rhythm in the precipitation which Liesegang gives, is that each ring of precipitated silver chromate which has been

formed, attracts material by diffusion from both sides. Other explanations have also been given, but in any case it seems certain that the rhythm is caused by diffusion.

As the spheroids of orbicular rocks are not formed by precipitation caused by the interreaction of two substances of which one is spread from the centre, the analogy with these phenomena cannot be complete. Therefore, in the present case, a gradual decrease of the distances of the rings, or shells, is not to be expected.

The analogy, again, lies in the fact that in both cases diffusion has played a prominent part. But in the orbicular granites, the rhythm seems rather to have been caused by a fractional crystallization under conditions which have hindered a free diffusion, i. e., by a high viscosity of the magma.

THE PRESENT AUTHOR'S EXPLANATION OF THE ORIGIN OF ORBICULAR STRUCTURES.

In the simplest cases, as represented, among the present rocks, by the orbicular granite of Puutsaari, or, by the Stockholm and Spitzbergen granites, there is mainly an aggregation of plagioclase, mixed up with some other minerals, around nuclei of a granitic or dioritic material. The plagioclase is preponderantly radially arranged and is mixed up with quartz, some mica, microcline etc. The radial arrangement is fairly similar to that of the microspherulites in porphyritic rocks, and both phenomena may be due to the same causes: rapid growth of the plagioclase in a magma containing it in great quantities, usually in a medium the viscosity of which is great.

In the bigger spheroids showing a concentric structure, especially in the Kangasala and the Virvik rock, the rhythm in the deposition of sialic and femic layers is very marked. There is, in the former, often an obvious proportionality in the mineralogical composition of two adjacent shells. If the inner-lying is very rich in mica, then the following consists of almost pure feldspar. The border towards the next biotitic shell is not quite so distinct and the sharp contrasts between the adjacent shells may gradually be attenuated.

If the rhythm in the crystallization of both minerals were due mainly to eutectics, then we should expect to find a regular intergrowth of them, analogous to pegmatite, micropegmatite and similar structures. We should also, as remarked earlier, expect to find such structures more commonly, if they were not due to more exceptional causes. Where the biotite crystals are more evenly dispersed, it may

still be possible to think of eutectics as an explanation, but when almost monomineralic broad zones alternate, it seems obvious that each mineral has crystallized alone in such quantity that the nearest-lying shell of magma was almost depleted of the components of the same mineral. In general, the proportion of the minerals composing the shells is very varying. Those portions of the spheroids of the Kangasala rock, in which the femic and sialic constituents are as independent of each other as the warp and weft of a web, are also strongly indicative of the simultaneous existence of two fractional magmas.

Morever, we find the same differentiation, in a portion rich in feldspar and another rich in biotite, also in the cement, both of the Kangasala, the Esbo and the Virvik rocks, and in these cases there can be no doubt that it is due to fractional crystallization, the sialic mineral having been the first to crystallize, followed subsequently by the femic minerals.

If it is true that the rhythm is due to fractional crystallization, it means that the material of each individual shell was always derived from the nearest surrounding zone of magma. Had there been an unhindered diffusion of the character admitted for the common magmas, such differentiated magma shells could not have existed.

Therefore, this reasoning leads, in different ways, to the conclusion that diffusion has been slow, i. e., that the magma of the orbicular rocks has been uncommonly viscous.

If that is so, then *the ending of the crystallization of the spheroids* means that the magma has assumed a different composition, so that the conditions for the formation of the spheroids have ceased to exist. In fact, we find a very marked difference in grain, occasionally also in composition, between the spheroids and the surrounding cement. It is commonly much more coarse-grained, in some cases pegmatitic. Such is a great part of the cement of the Kangasniemi rock, and also, although in a less conspicuous way, in the Hankasalmi rock and the variety of the Virvik rock with small spheroids surrounded by one dark shell. Even in the Esbo rock, where there is no marked difference in chemical composition between spheroids and matrix, the latter is much more coarse-grained than the former.

What is the cause of this sudden change in the conditions of crystallization? If the origin of the spheroids is due to a high viscosity, we must assume that it had been reduced, when the cement began to crystallize. This may be because all the water vapour and other mineralizers had gathered in the portion which was the last

to solidify. By the proportion of 60 to 40 of spheroids to cement, the amount of mineralizers, or »ichor», had been more than doubled, when the crystallization of the former was ended, provided that only small quantities were taken up in the spheroids, and no gases escaped. Thus, a point may have been reached at which the viscosity was so much reduced that the magma by being diluted obtained a pegmatitic character.

When microcline is present, it is usually much more abundant in the matrix than in the spheroids where it is, when it does occur, mainly heaped up in certain shells. The former fact seems to suggest that the potash feldspar longer remained in solution than the plagioclase, when the magma contained much water, or other gases. This seems to be a general phenomenon and may in part account for the fact that the microcline is later in most granites than the plagioclase. In dry magmas, as that of the rapakivi granite, the contrary phenomenon is observed.

The connection between biotite and microcline is very conspicuous in the inclusions of the bigger plagioclase crystals in the Esbo granite (fig. 2, plate XIV). These minerals cannot have crystallized earlier than the surrounding plagioclase. Their delimitations seem rather to indicate that they were formed out of small residual drops of magma enveloped by the plagioclase.

The main point in the above theory is the differentiation by fractional crystallization which leads to the formation of fractional magmas with a limited miscibility. Even in the case of fluids that are easily miscible, it takes a certain time before diffusion is able to mix them completely. They may long be separated by a pretty sharp boundary, as is shown by some of Liesegang's experiments. However, it is only when the internal friction is great that they become, as in the present cases, more definitely separated.

Rosenbusch already used, for a special case, a conception similar to that which has been here applied. He wrote the following, when referring to the orbicular diorite of S. Lucia di Tallano near Sartene in Corsica. His remarks are here given in translation: »The locally rapidly progressing crystallization of portions rich in pyroxene and hornblende caused the surrounding magma to become disproportionately rich in feldspar which rapidly crystallized as radial aggregates. Their crystallization, again, caused a local supersaturation of magma rich in iron and magnesia, so that again pyroxene and amphibole crystallized, and so forth» (73, p. 253).

If Rosenbusch and his followers had consequently drawn the conclusions out from these observations, their ideas about differentiation

might have taken an entirely different direction. Rosenbusch, however, declared his adhesion to Bäckström's hypothesis and accordingly explained the spheroids of certain orbicular granites as drops of a supersaturated solution in the magma, which formed a more basic differentiation of magma, and later crystallized from without inwards while swimming in the magma.

Rosenbusch's Kern hypothesis might also have been entirely modified, if he had followed the trend of mind expressed in the observations quoted above.

RELATIVE IMPORTANCE OF PLAGIOGLASE AND BIOTITE. PARALLEL TEXTURE OF THE SHELLS.

Frosterus thinks that the formation of the shells of the orbicular granites of Kangasniemi and Virvik was mainly determined by the crystallization of the feldspar, while the biotite crystals, which crystallized earlier and not alternately with the plagioclase laths (»nicht .... in successiver Folge mit den Plagioklasstäbchen auskrystallisierten»), were carried away by the plagioclase during its crystallization and thereby in part arranged in concentric rows around the spheroids (29, p. 29).

In fact, it seems to be true that the plagioclase, in general, plays a greater rôle in the crystallization of the spheroids and is more indispensable to their formation than the biotite. But the latter has not merely played a passive rôle. As to the Kangasala rock, there is no doubt about the alternative crystallization of layers of feldspar and biotite, and also in other orbicular rocks the same seems to be the case. The biotite does not always form idiomorphic crystals, but is very often xenomorphic towards the feldspar, and its position is very varied in different layers. In the thicker of those layers that consist mainly of biotite crystals, these lie in different positions, to a great part radially. The biotite of the thinner layers of the spheroids, again, is often to a great part arranged peripherically, especially where they form continuous rows.

The biotite crystals of the coarse, pegmatitic portions in the cement of the Kangasala granite are, where their growth has started from the periphery of the spheroids, attached to them by their prismatic surfaces and have grown mainly along their basal planes. In the same way mica grows when freely crystallizing in cavities. In the thinner layers, again, and also in the outermost parts of the thicker layers, the mica flakes often lie along the periphery. In the shells of the Esbo rock, the biotite crystals lie in different directions.

It is very difficult to account for this different behaviour of the biotite flakes. This problem is at the same time of great theoretical

interest, because the arrangement of the biotite flakes in concentric rows along the periphery causes a very perfect schistosity and cleavage to be developed which follow the boundaries of the spheroids of the different shells. Many spheroids of orbicular granites present the most typical example of a schistosity caused by a parallel arrangement of the biotite flakes which has nothing to do with pressure.

What, then, is its cause? It seems natural that in all cases where there is scanty room, or scarce material available, the biotite must grow especially along its basal plane in the direction which allows its freest expansion. In narrow fissures we also often find not only mica, chlorite, etc., but also other minerals coating the walls.

In rocks which have been dislocated there will be, at every movement, one component following the parallel structure and influencing the orientation of the mica crystals. In schistose stratified rocks, this orientating influence will, of course, be very much stronger than in the present cases, but also in these cases the crystallographical properties of the biotite are probably often more important than the mechanical pressure.

DEFORMATIONS OF THE SPHEROIDS.

The deformations of the spheroids provide much evidence as to their state during the last period of the consolidation. In a few exceptional cases the material of the outermost shells seems to have been in a slimy condition, forming an emulsion of small crystals, at an epoch before the final consolidation.

In other cases, again, the outermost layer has been shaven away from the others, when it was obviously already in a solid, or semisolid state.

In general, we find the most convincing evidence that the spheroids were solid bodies, when the matrix began to crystallize. The small crystals of the Virvik rock have been taken up by a magma stream, where they now lie scattered, while the orbicular rock has been in part refused (fig. 1, plate VIII). Some spheroids in different orbicular granites, especially the Virvik rock, have suffered lesions by the impact of other spheroids (fig. 2, plate VIII), and a great many have been deformed by the same process (fig. 1—2, plate IX, fig. 1—2, plate X, fig. 1, plate V etc.). They have in a great measure been resorbed, in the same way as fragments lying in a magma (fig. 2, plate VIII). On the eroded spheroids new layers have been deposited unconformably (fig. 2, plate IX). They have occasionally taken part in torsional movements around the original nucleus (fig. 1, plate

X). They have split up, so that narrow vein-like strips of granite could penetrate between the individual layers (fig. 1, plate V, figs. 1—2, plate IX, fig. 2, plate VIII etc.). They have, in exceptional cases, been cut by veins which have given access to the surrounding magma of the cement, or an outlet to the portion of magma which surrounded the central fragment, so as to be united with the magma lying between the spheroids (fig. 8).

If there is no doubt that the spheroids were deformed, while they were solid bodies, it is, on the other hand, obvious that they were not entirely solid, but possessed a certain plasticity. This may be explained in different ways, either by an incomplete crystallization, so that there still remained, between the crystallized minerals of the spheroids, small portions of fluid magma, or also by a subsequent partial refusion. The former seems more probable, because there is other evidence of a circulation of magma in the spheroids before the final consolidation of the rock. The formation of deuteric muscovite has been caused by pneumatolytic agencies which may have, too, made the rock of the spheroids more incoherent. Lastly, if we were to assume that the plasticity were similar in character to that pseudoplasticity which solid rocks show, when subjected to strong orogenetic pressure, then at least capillary fissures must have been opened in the mass of the spheroids.

REAL CATACLASTIC CHANGES.

The minerals of many of the orbicular rocks studied, however, show no signs, or only very feeble ones, of a cataclasis which has acted on perfectly solid rocks. Their changes are not due, as von Chrustschoff thought (18), to a real orogenetic pressure (»Gebirgsdruck»), but to epimagmatic processes. The Hankasalmi rock, alone, shows real cataclastic changes, such as we observe in gneissose granites. In fact, it may be designated as a gneissose orbicular granite.

The cataclasis is not well visible macroscopically, but the more so microscopically. We here observe the most typical mortar structure, the subdivision of the quartz in rounded grains, the formation of secondary biotite, etc.

It does not seem probable that these changes may have taken place very much later than the primary crystallization, but they are rather to be regarded as such metamorphic processes as have been connected with the intrusion of the same series of granites.

The interest of the Hankasalmi rock lies in the fact that we are able here to study these changes on a rock, the primary structures of which are so characteristic that they are easily recognizable also in the changed rock and thus offer an excellent opportunity of comparing primary and secondary features.

Table VIII.

	1	2	3	4	5	6	7	8
	Esbo, Shell of a spheroid	Esbo, Cement	Esbo, Average composition	Kangasala, Spheroid	Kangasala, Cement	Kangasala, Average composition 60 % of 4, 40 % of 5	Hankasalmi, Average composition	Virvik, Spheroid
SiO_2	56.13	57.26	56.91	57.21	65.57	60.44	61.84	54.59
TiO_2	1.86	1.08	1.47	0.49	0.56	0.52	0.43	
Al_2O_3	22.15	23.64	22.97	24.31	19.77	22.46	20.57	21.26
Fe_2O_3	0.79	0.39	0.59	1.30	0.16	0.84	0.26	2.76
FeO	3.62	2.45	3.05	1.87	1.58	1.75	2.45	3.41
MnO	0.01	0.01	0.01	0.05	0.01	0.03	0.03	
MgO	0.43	0.11	0.27	1.39	0.08	0.87	1.02	1.61
CaO	5.80	5.72	5.78	4.39	3.03	3.84	4.42	4.84
Na_2O	5.74	6.00	5.89	6.07	5.02	5.64	4.82	6.36
K_2O	2.34	1.96	2.16	2.01	3.70	2.69	3.27	4.96
P_2O_5	0.06	0.09	0.08	0.12	0.13	0.12	0.13	
H_2O +	0.57	0.76	0.67	0.76	0.34	0.59	0.62	
H_2O +	0.15	0.15	0.15	0.22	0.20	0.21	0.09	1.32
	99.65	99.62	100.00	100.19	100.15	100.00	99.95	101.11

	9	10	11	12	13	14	15	16
	Virvik, Cement	Stockholm, Shell of a spheroid	Stockholm, Nucleus of a spheroid	Stockholm, Surrounding granite	Slättmossan, Spheroid	Slättmossan, Surrounding granite	Kortfors, Spheroid	Kortfors, Cementing granite
SiO_2	69.21	67.88	72.20	70.67	53.77	56.97	55.72	70.05
TiO_2					1.21	0.68	0.57	0.19
Al_2O_3	15.59	17.56	13.98	14.80	20.86	20.96	21.35	14.78
Fe_2O_3	1.08						—	—
FeO	1.29	—	1.19	3.07	5.93	3.28	8.81	3.37
MnO							0.36	0.22
MgO	0.11	traces	traces	traces	2.76	0.77	0.63	0.44
CaO	1.30	4.18	2.98	1.33	5.04	6.58	5.10	3.42
Na_2O	1.69	4.88	4.08	2.51	5.01	6.63	5.71	3.10
K_2O	8.92	4.29	3.90	8.26	2.87	2.91	1.23	4.13
P_2O_5								
H_2O +								
H_2O +	0.75				1.86	1.96	0.46	0.42
	99.94	98.79	98.33	100.67	99.31	100.74	99.94	100.12

	17	18	19	20	21	22	23
	Romsaas, Spheroid	Romsaas, Cement	Romsaas, Surrounding norite	Altai, Shell of a spheroid	Altai, Nucleus of a spheroid	Altai, Cementing granite	Dehesa, Spheroid
SiO_2	51.55	61.28	50.81	62.84	65.57	68.27	40.08
TiO_2	0.58	0.40					
Al_2O_3	4.45	21.58	8.86	21.32	17.46	15.59	22.86
Fe_2O_3	0.50	0.22	3.17				
FeO	14.50	1.59	8.90	1.84	4.15	2.13	11.96
MnO	0.50	0.20	FeS 3.88				
MgO	22.08	1.85	16.49	0.56	2.53	1.19	12.40
CaO	2.61	7.51	4.40	3.51	2.49	1.93	11.41
Na_2O	0.64	4.44	1.18	4.16	2.14	3.21	1.26
K_2O	0.56	0.74	0.99	6.17	4.23	5.37	0.38
P_2O_5	0.11	0.52	0.51				
H_2O +							
H_2O +	1.28	0.40	0.95	1.13	1.26	1.56	
	99.36	100.77	100.14	101.53	99.83	99.25	100.35

THE CHEMICAL CHARACTERS OF ORBICULAR ROCKS.

The present rocks are so rare in occurence and so exceptional in their characters, that it seems probable that they may also possess an exceptional composition. A chemical investigation shows this to be true. They show characters that are not, or at least very seldom, found in any other rocks.

In table VIII, a number of typical analyses of orbicular granites, diorites and gabbros, of their spheroids, cement, etc., are tabulated. While the granites surrounding spheroid-bearing rocks show a fairly varying composition, not differing from that of common igneous rocks, and the same is true also of the nuclei, when they are composed of fragments of foreign rocks, we notice, at the first glance, that the shells of the spheroids possess rather a peculiar composition. They are high in Al_2O_3, Na_2O and CaO, while the contents of K_2O vary, being sometimes very low, and commonly much higher in the matrix and the surrounding rock than in the spheroids.

The contents of femic constituents also vary, especially the amount of MgO. Only in the orbicular gabbros, which are much rarer than the orbicular granites, is it high, and the feldspar is here rich in anorthite, while it is in the most common types an oligoclase.

According to the C. I. P. W. classification, the »orbicular granites» belong to different subdivisions. According to Niggli's classification, many of them might be diorites, but their composition is very different from that of the current types in this group. No classification has a ready made subdivision for rocks of this character. They form a rather independent group, corresponding, in relation to the diorite group, to the anorthosite-ossipite groups in their relations to the gabbros, according to Niggli's classification. As the rocks of the composition in question seem usually to be orbicular, these rocks might even be designated as o r b i c u l i t e s. As there are, however, also some orbicular rocks with a different chemical composition, it may be preferable to designate rocks of this magma type, i. e. oligoclasitic diorites, as e s b o i t e s, after the rock from Esbo.

This magma has, however, as has often been emphasized, an exceptional character and has not, quantitatively, the same importance as other magmas. Among those magmas which really occur as greater masses solidified in the form of igneous rocks, the esboite finds no place, but it may rather take its modest position by the side of lamprophyres, fenites and other similar ambiguous rocks.

For that reason, too, it is difficult to describe them as igneous rock types in the common sense, that they lack homogeneity, their different parts often showing a very varying composition.

The analyses clearly express the fact that the spheroids of orbicular rocks are commonly rich in plagioclase, while the other constituents are not equally indispensable to the formation of these structures. This plagioclase is in many cases fairly rich in albite. Only in the gabbroid and some of the dioritic orbicular rocks is it more anorthitic in composition.

If it were only the richness in plagioclase that determined the formation of spheroids, they might be expected to occur also among anorthosites or »ossipites», where, however, they have not been found. These rocks have often been derived by fractional crystallization out of a magma which approximates a basaltic composition. Such a magma has probably, in most cases, crystallized at a much higher temperature than the granitic magma rich in mineralizing gases and fluids, and has been more easily fluid at the moment when it began to solidify.

Where orbicular structures occur in rocks containing anorthitic plagioclase, and in those approaching a gabbroid composition, there often seem, anyhow, to have existed conditions which were near to those prevailing in granitic magmas. The orbicular gabbroid rocks occur as smaller portions, surrounded by great granitic masses, or at the contacts of the basic rocks. The latter is the case, e. g., with the peculiar occurrence of orbicular gabbro at Askim near Romsaasen in Norway (18, 56, 88).

The typical magma of orbicular rocks does not, however, possess a gabbroid character, but is rich in a plagioclase containing much albite. Such a magma must necessarily have been very viscous.

Day's and Allen's experiments (22) show that while melted diopside flows like water, thin rods of albite which have been heated to 1.300 during several hours and have become entirely isotropic, still remain so rigid, that no bending occurs. This seems to indicate an uncommonly high internal friction of this melt. Although molten orthoclase is very viscous, too, it seems probable, as explained above, that it joins more readily with the solvents of the magma, and that circumstance may lower its viscosity. Potash feldspar therefore forms part of the mother-liquor that solidifies as a matrix between the spheroids.

Greiner's experiments (34) show that in a melt of $NaSiO_5$. SiO_2, an addition of Al_2O_3 or SiO_2 adds to the viscosity.

The idea that the formation of the spheroids was favoured by a high viscosity, seems, therefore, to be in harmony with the chemical data. As has been pointed out, this character is, perhaps, not absolutely indispensable, as fractional magmas formed by crystallization

may sometimes, perhaps, remain separate for a time sufficient to crystallize, even if the adjacent magma is not highly viscous. Such a character must, in any case, be very favourable to their formation.

It is not a general disharmony in the chemical composition that accounts for the formation of orbicular structures, but a composition of rather definite character, and which is seldom to be found.

Some orbicular rocks, e. g. among the Japanese granites mentioned at the end of this pamphlet, seem to be fairly different from the others as to their mineral composition. The greatest part of the orbicular rocks, however, are very nearly related, and connected by transitional varieties.

ORIGIN OF THE ESBOITIC MAGMA.

The magma of the orbicular granites usually forms »Schlieren» or small cloud-like masses in a purer granitic magma. These may sometimes, as e. g. in the Puutsaari rock, be very small, but even the biggest masses seem not to exceed 100 m in diameter. They have, thus, really the character of something exceptional, fortuitous. How have these magma clouds originated?

The first explanation to take into consideration is the liquation hypothesis. In regard to the present case, there is no fact speaking in its favour. If such clouds of magma with prevailing plagioclase were to originate by liquation in granitic masses, it is difficult to understand, why they should be so rare. We should then also expect to find intermediate stages, so that they would gradually fade into the surrounding granite.

If, again, the accumulation of plagioclase material were due merely to a differentiation by fractional crystallization of a common granite, it would be necessary to assume that a very great quantity of the surrounding granite, which is in itself very poor in plagioclase, would be deprived of these constituents. There is no evidence in the surrounding granitic masses of a corresponding change in their composition. On the contrary, they possess the composition which is usual in the Hangö granite areas.

It seems fairly probable that the magma was of a hybrid character. In many of the orbicular rocks containing spheroids, fragments of basic rocks are exceedingly common, and occur in all stages of dissolution. Earlier authors, especially von Chrustschoff, have also suggested that a hybrid character of the magma had an important bearing on the formation of orbicular rocks.

By the study of the granites of southern Finland which most commonly contain orbicular structures, overwhelming evidence has

been found proving that basic rocks have been assimilated by them, but in general in such a way that the products of the syntexis have been rapidly removed by diffusion. Syntectic rocks occasionally occur, too, e. g. at the contacts of the Obbnäs granite described by the present author (82), but in them an accompanying differentiation has taken place. Their composition is, therefore, by no means, a medium between that of the assimilating and the assimilated rock. The cause of this rapid removal of some portions of the symmict magma still appears enigmatic.

The author is at present studying certain phenomena which he hopes will give a clue to the explanation of the differentiation processes connected with the anatexis. In any case, the existence of facts pointing in this direction is undeniable. Basic rocks have been assimilated, and their femic and sialic parts have often begun to separate already soon after the dissolution (cf. fig. 4 in the text and fig. 2, plate II, of the present paper and their description, pp. 8 and 10).

Under exceptional conditions, products of the assimilation processes rich in plagioclase may have remained in place and the magma received an unusual composition.

In the present case, the fragments which are numerous in the surrounding granite and also occur in the orbicular rocks themselves, possess a metabasitic character, and a basaltic, or gabbroid composition. No syntexis of this rock and a granite can give a rock which has the composition of the orbicular rock masses. In order to get a sufficient amount of plagioclase, great masses of the basic rock must be added which would increase the amount of femic constituents very much. Only if these have been removed during the anatexis of the fragments, the products may reach the composition of the orbicular rock. That they have been removed, seems to be undeniable, supposing that the rock has a hybrid character, but in what way, remains to be explained.

Whatever may have been the first origin of the esboitic »magma cloud», it seems probable that it has undergone some kind of refusion before the formation of the orbicular structures began. The preexisting plagioclases have, thus, been changed into components of a new magma, the solidification of which began again later.

MICROSPHERULITES AND MACROSPHEROIDS.

Von Chrustschoff defines the orbicular granites as macrovariolitic rocks (18). In fact, there is, as already remarked, a pretty close analogy between variolitic and microspherulitic structures of dif-

ferent character, on the one hand, and certain types of spheroids, on the other.

Let us quote what Harker says about spherulitic structures (35, p. 272): »The essential feature of spherulitic structure, as Iddings remarks, is crystallization about a centre, or a number of neighbouring centres, with a divergent or radiate arrangement. The growth may or may not terminate at a sharply defined outer boundary. — — — A spherulite does not crystallize at a point of time, but grows from the centre outward. — — — The radiate arrangement is the essence of the spherulitic structure. The fibrous habit suggests that the spherulites crystallized rapidly in a highly supersaturated solution, and this was doubtless their mode of origin. When they are embedded in glassy or devitrified matrix, the flow lines are seen to pass interruptedly through the spherulites, and, indeed, the latter may sometimes be seen to have formed subsequently to brecciation of the rock. In such a case the matrix was a glass rather than a liquid, when the spherulites crystallized. The crystallization at isolated centres doubtless depended upon local richness in dissolved water-vapour, reducing the viscosity in those places.»

In any case, it is generally admitted that the spherulites crystallized in a viscous medium, and they would thus be genetically similar to the simpler spheroids consisting mainly of plagioclase laths.

There is a figure of a spherulite in Jeremine's and Loewinson—Lessing's description of volcanic rocks of the Mugodjaric Mountains in the Caucasus (53, fig. 5) which very much resemble those of orbicular structures, and this similarity is probably not a casual one.

If there is an analogy between spheroids and spherulites, then there may also be, as Borgström has thought possible (cf. p. 47), another, although still more vague analogy between spheroids and c h o n d r e s of meteorites. These are certainly spherulitic structures, and it is often thought possible that they may be solidified drops of magma which have crystallized during the flight through an athmosphere that has either been very hot, as Sorby and Wahl think probable, or also, according to Borgström, very thin. There are, however, e. g., in the Bjurböle meteorite described by Ramsay and Borgström, chondres which show no definite boundary against the surrounding rock, and in that case it is difficult to imagine that they could have ever existed as isolated drops of magma. The present writer does not see any reason why the chondres could not have originated in a rapidly cooling magma, in almost the same way as common spherulites. They may possibly, in some cases, have been surrounded by spheroidal cracks.

In any case, the chondres are due to a very rapid crystallization under exceptional conditions, and their mode of formation is so little known that it is difficult to use their explanation for throwing light on the spheroids.

BEARING OF THE THEORY PROPOUNDED ON DIFFERENTIATION.

The orbicular granites, no doubt, present a very typical case of differentiation. How far is it, then, possible to give to the explanation of their origin here proposed a wider application, using it also for the larger magma masses? It is true that the conditions under which these peculiar rocks have solidified, as well as their chemical composition, are so exceptional that it is rather improbable that the same conditions have existed in larger magma basins, when these have undergone differentiation. Anyhow, the study of the orbicular rocks may help to develop the methods of the investigation of the differentiation phenomena, and to eliminate erroneous ideas as to their explanation.

The rare cases may, in general, throw a sidelight on many difficult questions and give suggestions also as to the interpretation of the more common phenomena.

The fractional crystallization which we here meet with in such a typical form, seems to the present writer to have been the c a u s a a g e n s also of most other differentiation phenomena in the magmatic rocks, at least in the cases known to him from his own country. Such is the case with the formation of inclusions of anorthosite and of the granitic veins in diabases and ossipites, which outcrop on the Åland Islands, on the shores of the Gulf of Bothnia, and on the islands of Lake Ladoga, further, the differentiation of granite, gabbro and peridotite in Ruskeala in Eastern Finland, in the neigbourhood of Jyväskylä in Middle Finland and in Ylöjärvi in Western Finland, etc.

The differentiation which the present author has studied in composite dykes, consisting of alternating zones of »epibasite» (lamprophyre) and aplite, is probably also due to fractionation. In any case, this theory seems to be the best working hypothesis for the explanation of these dyke rocks.

While his conclusions thus point in the same directions as those at which Bowen and other representatives of the American petrological school, have arrived (6, 7), he differs from him, however, as to some details of the explanation. Bowen places much importance on the idea which was put forward already by Charles Darwin, that the sinking of heavier crystals, like a snowfall within the magma, may have caused a heaping up of them in the deeper parts of the magma basins,

thus making them more basic than the upper parts. To the present author, the evidence in favour of this assumption seems too scanty to allow of its more general application, and he is inclined to infer, from the experience gained during the present studies, too, that viscosity has been too high, at least in most plutonic magmas, to allow of a free sinking of single crystals. It seems more probable that partly crystallized rock masses may rise or sink as a whole, according to their lighter or heavier minerals having crystallized earlier. The residual portions of the magma may escape, because of their being accompanied by the gaseous or fluid mineralizers, as has been emphasized by Harker (35) and Evans (26). This process has been called a »squeezing», but it could also be designated as a kind of d e c a n t a t i o n. Harker has, already earlier, used that word, although not as a term.

Moreover, Bowen, like several other American petrologists, derives the granitic magmas from a gabbroid mother magma, a conception which is very different from those which the present author has tried to develop. It seems to him more probable that the granitic masses forming the upper parts of the lithosphere, and the underlying more basic magma, have existed separately since the early date when the molten globe began to be covered by a solid crust. Later, too, there seems to have been a certain antagonism between the basic and acid magmas. Where we find basic and acid rocks which have been formed by differentiation of the same magma, this has more often a granitic, or granodioritic, than a gabbroid composition.

In general, the conceptions of the present writer are near to those which Harker developed during the discussion on differentiation at the International Congress of geology in Canada in 1913.

In none of the cases studied by the present writer has he been able to find any evidence in favour of a »l i q u a t i o n». He will not deny the possibility that this process may have played a part, by the formation of magmas of different composition. The reasons on which such assumptions have been made, seem to him, however, in many cases very insufficient. The use of statistical methods especially, with the aid of diagrammatic plottings, are often apt to lead to deceptive results, as long as the mathematical treatment has not been preceded by a strict logical discussion of the problems which are to be elucidated by the statistical figures. Mathematics are of little aid, in natural science, if the premises have been wrongly stated.

Lastly, as liquation remains a fairly enigmatic process, while fractional crystallization is a thing which we often observe, and

which certainly has taken place also in rock magmas, it may be safer to start from this end, and to try first, how far this simple explanation is applicable. If it fails, we may look for other theories.

The present writer will not, in this connection, enter into any discussion of the application of Soret's principle for explaining the differentiation phenomena. Like Harker, Bowen and many others, he finds it inadequate for this purpose.

SPOTTED AND NODULAR GRANITES ETC.

SPOTTED GRANITES.

The spotted granite, granite tacheté, Lacroix (49), is a phenomenon which has also been compared to the orbicular granites. It really occurs, in Stockholm, in very typical form in the same granitic mass which occasionally shows an orbicular structure. As it follows from the description of it given by Geijer (30), there is, however, no genetical connection between the two phenomena. The spotted granites occur at several places in the city of Stockholm, and in its neighbourhood. In the biotite-granites irregular spots are visible which consist of an aplite that often contains titanite. Some of them contain a darker central portion rich in biotite, while the surrounding white zone is composed only of feldspar, mainly microcline, and quartz. In other cases, the central part is rich in titanite, mixed with some pyrite.

Geijer regards the spots as aplitic segregations, genetically related to the aplitic veins in the same granite. The aplitic parts of the granitic magma have gathered at certain places and have changed it autometamorphically. He thinks that a differentiation began already when the granitic magma was fluid, but also compares the spots to the fillings of miarolithic cavities.

The present author thinks it possible as well, that the aplitic solutions pervaded the rock, when it had already in great part solidified. He has found, in the Stockholm granite, also small angular fragments of gneiss which are surrounded on all sides by a rim of similar aplite which has probably been formed by a process of replacement.

Lacroix earlier described similar phenomena from the Pyrenees (49). In this »granite tacheté», the feldspar of the nodules is, however, mainly plagioclase.

In similar nodules described by Lincio from Roccapietra in Italy, the central parts contain tourmaline and are surrounded by a white aplitic rim.

The occurence of pneumatolytic minerals in the centres of these spots, is an important fact, indicating that these portions of the magma were rich in gases.

NODULAR GRANITES.

Geijer regards the spotted granites as analogous to the granites containing well defined and rounded n o d u l e s of quartz, often associated with muscovite and sillimanite and also with tourmaline. Such rocks have been described by Adams from Pine Lake in Ontario (1), by Brögger from Kragerö, and by Geijer from Pajala in Northern Sweden and from the Sydvaranger ore district in Northern Norway (31).

Eskola has found quite similar, well rounded quartz nodules in a gneissose granite from Enontekiö in Northern Finland. It is remarkable that the stripes rich in biotite, which mark the schistosity of the granite, continue through the well marked nodules.

Adams thinks that the formation of the nodules has begun by the gathering of drops, through liquation, before the crystallization of the rock, and compares them to the spheroids of the orbicular rock from Kortfors (1). Vogt thinks that they are due to eutectic conditions (90). Geijer, again, regards them from the same point of view as the aplitic spots, but thinks it possible that there may have been a limited miscibility in the magma.

When this pamphlet was in preparation and nearly ready for printing, the present author was fortunate enough to find a new locality of a very typical nodular granite, which seems to give a definite answer to the question about their origin.

In the northern part of the parish of Kumlinge, among the Åland Islands, there is a solitary island called Stor-Klyndan. It is composed of granites belonging to the Hangö—Nystad types, or the second group in the classification of the present author of the granites of Southern Finland. They are here in part grey, in part reddish, and mostly massive. Pegmatitic and aplitic dykes and veins, as well as such approaching a lamprophyric composition, occur, but the greater part of the rock masses is fairly homogeneous. There are, however, in places very big fragments, measuring several hundred metres in length, of migmatitic rocks, composed of a schistose component, very rich in biotite, and numerous veins of granite. It is dificult to decide, whether this granite belongs to a geologically separated older group, or simply to earlier erupted parts of the rock masses which form the main part of the island. In any case, it is somewhat older than the surrounding granitic masses. The fragments were migmatites already when they were included in this granite.

The aplitic dykes and veins contain nodules of a mass rich in quartz. They have an ovoidal shape and attain a length of about 3 cm and a breadth of 2—3 cm (fig. 14 and fig. 1, plate XI). It is a nodular granite of the most typical character.

The nodules consist of crystalline quartz and various amounts of sillimanite, forming numerous slender needles.

The nodules occur, however, not only in the granitic veins, but also in the surrounding schistose rock. Some of them occur on the border-line of both rocks, which makes it still clearer that all have a common origin. The nodules in the schist are often richer in sillimanite than those of the granite, and some of them consist almost exclusively of this mineral. Sillimanitic nodules in schists are of common occurrence, and there is hardly any doubt that they have

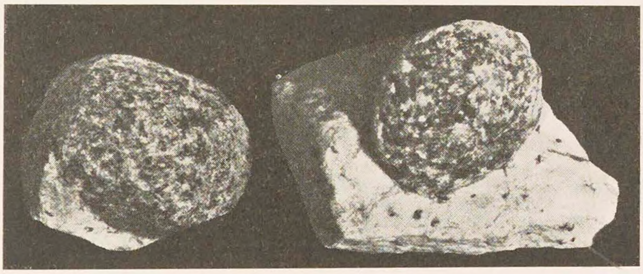


Fig. 14. Nodules of quartz and sillimanite in granite from Stor-Klyndan in Kumlinge, Åland Islands. C:a 2/3 nat. size.

an origin similar to that of contact minerals. In the present case, too, the nodules both in the schist and the granitic veins are, no doubt, due to the contact action of the surrounding granite.

These things have thus nothing to do genetically with the orbicular granites, nor can they be due to liquation phenomena in the magma during its solidification. They are certainly of secondary origin.

There is, as admitted by Geijer, an analogy between spotted and nodular granites. However, the former have been formed by processes which are probably due to epimagmatic processes in the same granitic magma, thus to be designated as »deuteric» phenomena. The nodules, again, are really secondary, due to the contact action of a rock which has been later intruded.

The present writer has observed phenomena which show some analogy to the spotted granites, in granites where aplitic and lamprophyric veins have been formed, at the end of the solidification of the

granitic magma, and through the influence of its »ichor», or »juices». Also the formation of garnet surrounded by aplitic aureoles shows a certain analogy to the »spotting».

NODULAR MICASCHISTS.

In the mica-schist of the Tulola island in Lake Ladoga, a rock which has undergone so strong a metamorphism that it has become massive like a granite, contains peculiar nodules which have been described by Blankett (5), Berghell (4) and others. Similar structures, which seem to have a certain analogy to the nodules of nodular granites, occur at many places in the schists of Eastern and Northern Finland.

The present writer has mapped the region around Tulola and repeatedly studied these structures. As a detailed description of the region next to Lake Ladoga, by Dr Victor Hackman, will soon appear, he will here only briefly mention these structures, publishing some of the numerous photographs which he has taken.

The nodules, which have ellipsoidal forms, usually measure 20—30 cm in length and 10—15 cm in breadth. In exceptional cases, they are drawn out to a greater length. Sometimes several may join, but most of them lie separately. The micaceous stripes in the schists may sometimes wind around the nodules, but often they go through them (fig. 2, plate XI).

The ellipsoids consist of a fine-grained rock in which quartz is prevalent. Oligoclase is, too, fairly abundant. Both minerals occur as grains which have diameters of 0.1—0.3 mm. Crystals of a reddish garnet and small grains of titanite are strewn over the mass. The latter mineral may be enclosed in the former. A hornblende, which is strongly pleochroic in yellowish-green to green, sometimes bluish colours, occurs as long skeletal crystals which have obviously crystallized later than the fine-grained minerals. Together with the hornblende, grains of calcite occur.

In many of the nodules a coarsely crystalline quartz, associated with crystals of green apatite, forms indistinctly delimited vein-like stripes, which may either lie on both sides of the nodules (fig. 15) or cut, them transversely, then often projecting at both sides a little over the boundaries of the nodules. In one case, a real, sharply delimited narrow vein of pyrite was seen in the midst of a nodule, cutting it transversely. It gave the impression of the nodule having shrunk during its solidification.

The rock containing these nodules has been designed as a »klot-skiffer», which should correspond to orbicular schist. It may be

better to call it a nodular schist, as these peculiar structures seem to be genetically related to the nodules of granites. There is little doubt that they are due to the secondary action of the granitic magma.

All these phenomena are better studied in connection with ultra-metamorphic and autometamorphic changes than with the study of orbicular granites. There may be a certain connection between a part of these phenomena, at least in such a way that they may interfere in certain rocks, e. g., in the Stockholm granite, but in the main they are genetically different.

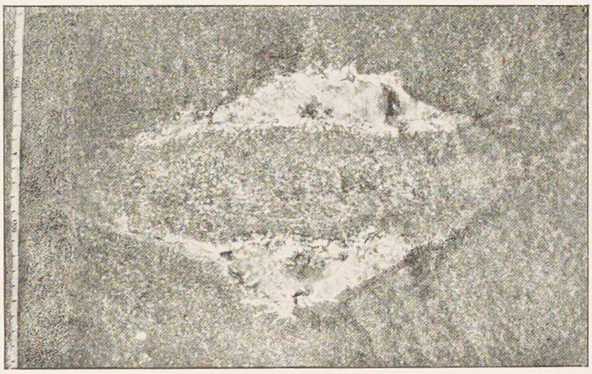


Fig. 15. Nodule of quartz, oligoclase, etc., in mica-schist on the island of Tulola, in Lake Ladoga, near Sortavala, C. 2/7 nat. size.

ORIGIN OF THE RAPAKIVI TEXTURE.

RAPAKIVI ROCKS AND RAPAKIVI TEXTURE.

As already said, the orbicular granites with small spheroids show much analogy to certain porphyritic granites.

Especially the typical rapakivi granite, which is characterized by the occurrence of well rounded crystals of orthoclase, surrounded by a shell of oligoclase, seems to show so much affinity to some of the phenomena here studied, that it is tempting to see, if the same theories that have been used for the explanation of the orbicular rocks, may have any application, too, to the study of the rapakivi. The writer has, however, no opportunity of going very deeply into this subject at present, but must restrict himself to some suggestions in a general discussion of the explanations which have been hitherto given of the peculiar texture of the rapakivi.

The rapakivi texture has been especially observed in granites belonging to a well characterized group of pre-Cambrian granites

which are genetically associated and show great petrological similarities in the different areas. The largest of these is the so called Wiburg (or Viipuri) area in S.E. Finland, the area N.E. of Lake Ladoga and the areas in S.W. Finland of which the northernmost was formerly designated as the Nystad (Uusikaupunki), but later as the Laitila area, and the southernmost Vehmaa area, further the Åland areas and the Ångermanland and Ragunda areas in Sweden.

Altogether, there are about ten areas in Finland and the same number in Sweden, although some of them are small. Probably, a granite of the region S. of Trondhjem in Norway, described by Carstens, is a rapakivi in metamorphic facies (16).

In most of the larger areas in Finland the typical rapakivi is the prevalent rock. The most coarse-grained variety occurs in the Wiburg area, the most fine-grained in the western part of the Åland area. Gradations to varieties which have no plagioclase shells around the ovoids, and to granite-porphyries and quartz-porphyries also exist, as well as equigranular varieties closely associated with the other rocks.

Chemically, the rapakivi granites are in general well characterized. Basic rocks occur closely associated to them, but it is doubtful, whether they are really, as has been assumed, differentiation products from the same magma. In many cases, at least, they are syntectic rocks formed by the assimilation of basic rocks which are somewhat older than the rapakivi.

The rapakivi granites differ from the majority of the older pre-Cambrian granites of the same regions in that they show almost exclusively primary features. They are practically devoid of cataclastic phenomena and, in most cases, also of those autometamorphic changes which the present writer ascribes to the influence of ichor, or what is usually called granitic juices, at the end of their crystallization. The formation of myrmekite and some similar structures, especially in the Wiburg rapakivi, is an exception to this general rule, and in some of the areas, especially that of Laitila (Nystad), aplitic varieties occur at the contacts, showing that the magma was uncommonly rich in ichor. Where such aplitic varieties occur, migmatitic rocks are also seen at the contacts with the older rock masses. In general, however, they are conspicuous by their absence, or comparative rarity, at the contacts of these big granitic masses which have obviously crystallized very near to the surface of the earth, by the cooling of sheet-like masses from which the greater part of the water vapour had already escaped. The rapakivi magma was a dry magma, and not in the same measure as many other granitic magmas a hydato-pyrogeneous melt.

Therefore, these rocks show the textures originated by the cooling of a granitic magma in an uncommonly typical form. They have been formed in one casting. It is not meant by this that a refusion and recrystallization may not have taken place during the first stages of the crystallization of the magma, but only that these rocks have not suffered any notable autometamorphic changes by the influence of granitic ichor. As they exhibit such peculiar features, they must have crystallized under circumstances which have seldom been repeated. They do not, therefore, strictly correspond to the primary types of the most common granitic rocks, which have in general crystallized out of a magma rich in ichor and the intrusion of which has very often been closely connected with orogenetic movements. There are, however, so many analogies between the textures of the rapakivi granite and those of granites which have solidified at greater depths, and with a greater content of mineralizers, or which have undergone stress during their intrusion, that the clear and distinct textures of the former may be used as a kind of standard for judging the granite textures which have a more dubious character.

The rapakivi texture is nearly akin to porphyritic textures, but the ground-mass is scanty in quantity and, in general, not so fine-grained as in granite-porphyries. The ovoidal shape of the orthoclases and their coating with an envelope of oligoclase constitute other differences.

While in many granites the oligoclase has crystallized earlier than the potash feldspar, the reverse has occurred in the typical rapakivi. In most rapakivi rocks, the crystallization of orthoclase has prevailed during the first stage of the crystallization, although often also quartz and plagioclase have crystallized simultaneously. In some varieties, the bigger feldspars are therefore microperthitic. In the typical rapakivi, again, the greater part of the plagioclase, as well as the quartz, and almost all biotite, have crystallized later than the main part of the orthoclase.

The size of the ovoids of the Wiburg rapakivi is about 2×4 cm on an average (fig. 16), but they may sometimes possess a diameter which is double or even more than that (figs. 17—18, figs. 2—3, plate XII). In the Åland rapakivi, they often measure less than a centimetre, but in the eastern part of that area there are also varieties which are as coarse as the rapakivi of the adjacent areas of the Finnish mainland.

The thickness of the oligoclase shells usually varies between 2 and 5 mm. The bigger ovoids often contain, besides many alternat-

ing shells of oligoclase, also shells rich in included grains of quartz or biotite.

For detailed data about the rapakivi rocks of the Wiburg area the latest treatise of Wahl may be referred to which also contains an interesting discussion of different theories of their origin (92).

Fig. 16. Rapakivi in a horizontal rock surface on the island of Työsaari, Lake Kivijärvi, Lemi, N.W. of Wiburg. C:a 2/5 nat. size.

As a term, the word rapakivi has been used in several different meanings. It was introduced as a geological term already by Daniel Tilas, when he carried on a geological survey in South-Western Finland in 1735 on behalf of the Swedish government. During it, he investigated the rapakivi areas of South-Western Finland and emphasized the peculiarity of this rock and its difference from the older granites. These researches were also noteworthy, because it was during them that he, as has been shown by Zenzén (96), first introduced the term f e l d s p a r. He had found, in the fields of the parish of Laitila (»Lethala») a great number of »spar» crystals loosened from the rapakivi granite by weathering, lying strewn over the fields in the region. He therefore called them f e l d s p a t (in modern Swedish fältspat) = feldspar. Before that time feldspar had been designated

as »hard spar», but the name feldspar had never been used for it. The word feldspar has thus nothing to do with f e l s, and the spelling feldspar is no doubt etymologically more correct than felspar.

The Finnish word r a p a k i v i means rotten or weathered stone, and it has therefore been applied, even by geologists as late as in the eighties, also to other varieties of coarse-grained and easily weathering granites than those genetically connected with the typical rapakivi granites. This use has, however, now ceased, and rapakivi is only used for granites belonging to a definite group of late pre-Cambrian rocks.

The word rapakivi has, however, been used in different meanings, both as a petrological and a geological term. As the rocks of the different areas of genetically connected rocks possess very similar petrological characters, they have often been called rapakivi-granites, even when they lack the characteristics of the typical rapakivi. As a geological designation it may be preferable to use the words L o w e r J o t n i a n (= sub-Jotnian, according to Högbom) or H o g l a n d i a n granites, proposed by the present writer (83).

Further, Niggli has used the name r a p a k i w i t e (better spelt rapakivite) as the designation of a magma of definite composition. This use does not interfere with the use of the word rapakivi in other senses.

For the term rapakivi, as designating a texture, substitutes have also been proposed. Holmquist calls the texture of the typical rapakivi m a r g i n a t i o n s t r u c t u r e (42). The meaning of the word margination, from marginare, marginer, does not, however, quite cover the idea which it is intended to express, and above everything in this instance a shell is meant, not a r i m of oligoclase, not a thing of two dimensions, but of three.

As the typical rapakivi texture is characterized by two phenomena which always occur together, the rounding of the orthoclases and their coating with oligoclase, it is difficult to designate it by a term referring only to one of them. Therefore, it seems preferable to maintain the use of the word rapakivi as a designation of this peculiar t e x t u r e.

Wahl has proposed to call the typical rapakivi from the Wiburg area W i b o r g i t (92). Although it would be convenient to possess a special name for this rock, the present writer fears that it would lead to an overburdening of the petrological nomenclature with names, if we should introduce different terms, formed from names of localities, not only for magmas of different composition, but also

for rocks characterized by different textures. If we followed this example, we should get a great number of names for the rapakivi rocks alone and also for the different orbicular rocks.

OLDER EXPLANATIONS OF THE RAPAKIVI TEXTURES.

Half a dozen different explanations of the peculiar rapakivi texture already exist which will be discussed here.

THE LIQUATION HYPOTHESIS OF HOLMQUIST.

Holmquist goes farther than anybody else in the application of the liquation theory (42). He thinks that not only spheroids of orbicular rocks may originate in this way, but that also the crystallization of a granitic magma, like that of the rapakivi, may begin with the formation of d r o p s, out of which each of the feldspar crystals later crystallizes. Also if we imagine that these drops crystallized exotropically, by the deposition of layer upon layer, beginning from a central nucleus, not eisotropically, as Bäckström thought probable in regard to the spheroids of the orbicular rocks, it is however, in both cases, necessary to assume that the repeated alternation of orthoclase and oligoclase shells in the feldspar ovoids also existed already in these drops, making them as manifold as the wooden eggs which children use as playthings and which contain a great number of shells of gradually diminishing size. If, again, we assume that the oligoclase shells have been formed by fractional crystallization, then the liquation theory becomes altogether unnecessary.

The liquation hypothesis applied in this case, has, however, a kernel of truth in that it assumes that the magma has in some cases differentiated in portions of varying composition already before it crystallized. Only, these fractional magmas were not formed by liquation, but call for another explanation.

POPOFF'S HYPOTHESIS OF GRAVITATIVE MOVEMENTS OF THE RAPAKIVI OVOIDS.

Popoff calls attention to the varying sizes of the ovoids, and draws the conclusion that they have crystallized at different places and later been mixed together (66). When small crystals had once been formed, they began to sink and arrived at layers of magma with a higher temperature. Here their corners and angles became rounded by melting, and the crystals got an ellipsoidal shape. When the diminished feldspar crystal arrived at lower regions of heavier magma, its sinking ceased and it became coated with other minerals:

oligoclase, quartz, biotite and hornblende, forming together a more or less continuous shell. Later, the crystallization of the orthoclase again began, when the temperature had been lowered, and the sinking of the crystal started anew. Such movements may have been repeated several times, and at each epoch of repose a concentric shell of inclusions was formed. When a greater number of ovoids simultaneously reached a zone, where crystallization of oligoclase was going on, they were all coated with oligoclase, occasionally mixed with other minerals. The crystallization of the oligoclase may have been accelerated by the cooling influence of the sinking orthoclase crystals.

Popoff also suggested that this theory of the sinking of crystals might explain the zonar structure and differentiation processes, and he is thus, as Wahl pointed out, one of the forerunners of certain modern theories on differentiation.

Wiik also, already earlier than Popoff (95), adopted a similar explanation, although he thought it more probable that only two layers of magma, possessing an altogether different composition, had existed.

Popoff's theory is certainly ingenious and suggestive, but it is difficult to bring it into harmony with several observed facts. If oligoclase and other minerals had begun to crystallize earlier than the orthoclase in the deeper zones, they should have been earlier also in the adjacent upper layer, when the latter possessed a higher temperature, and we should then expect to find them also as nuclei of ovoids, while they now always form the coatings of the orthoclase ovoids. Moreover, ovoids with a coating of oligoclase also exist at such places where no sinking has been possible. For instance, at the western contact of the greatest rapakivi area we observe well developed ovoids between fragments of rocks which form the roof of the laccolith, and even within the limits of fragments of meta-andesites that have been soaked with rapakivi magma (cf. the descriptions and figures given by the present author in 80, pp. 88—89). To the question whether we are able to account for the rounded shape of the ovoids by resorption, we will return later on.[1]

VOGT'S AND HARKER'S THEORY OF ALTERNATING RESORPTION STAGES IN A EUTECTIC MIXTURE.

Vogt regards the combination of orthoclase and oligoclase in the rounded feldspar crystals of the rapakivi as a eutectic mixture

[1] Popoff's interesting paper, Mikroskopische Studien am Rapakivi, etc., Fennia 50, N:o 34, which was published during the printing of the present pamphlet, could not be referred to in this discussion.

of both. When the point for the crystallization of orthoclase had been passed and plagioclase began to separate out of the solution supersaturated with it, the orthoclase was corroded and received its rounded shape (89—91).

Harker has developed similar ideas (35, pp. 267—268). He regards the rapakivi granites as the most remarkable example of the effects of supersaturation. The rounding of the feldspar, he thinks, is doubtless due to that. The alternations of orthoclase and oligoclase point to supersaturation of the magma with the two minerals alternately. Although it is true that in the ideal case of a binary magma supersaturation is no longer possible from the moment when crystals of both minerals begin to be formed, this does not hold good, if the crystals of orthoclase are covered with a layer of plagioclase, or conversely. In this case the indicating-point of the diagram may continue to oscillate about the eutectic points, until a number of alternating zones have been built up.

No doubt, a supersaturation of orthoclase and oligoclase alternately takes place, as admitted by Harker. Only, it seems more than doubtful, whether the magma out of which these feldspar ovoids crystallized, really possessed a eutectic composition. These parts of the mineral constituents, the composition of which is nearest to a eutectic mixture, have been formed in the magma, when it had its most complicated composition, containing also all the ferromagnesian constituents, and by no means corresponded to a eutectic mixture of orthoclase and plagioclase.

In all varieties of rapakivi, the ovoids of orthoclase covered with oligoclase have crystallized earlier than the cementing mass which entirely corresponds to the ground-mass of the porphyritic varieties and contains a second generation of orthoclase and plagioclase, but also most of the biotite. In certain varieties of the Åland rapakivi granites, the *druses* lie in the mass between the bigger orthoclase crystals intergrown with quartz crystals, and biotite and other minerals have *grown into* these cavities.

There is an obvious contradiction between Vogt's explanation of the porphyritic texture in general, and that of the rapakivi texture.

In the former case, the first crystallized minerals should represent the *surplus* over a eutectic composition, and the magma should approach the latter more and more during its crystallization. As Harker remarks, while discussing these matters from a similar point of view, we should expect the *groundmass* to represent the eutectic. Here, again, it would be necessary to think that the eutectic mixture was the *first* to consolidate, a conclusion en-

tirely at variance with Vogt's own views on the solidification of rock magmas. Another important point in Vogt's and Harker's theory is that they explain the rounded form of the feldspars by resorption which the present author thinks inadmissible.

WAHL'S THEORY.

Wahl has, in his important work on the rapakivi granites of the Wiburg area (92), propounded an altogether new theory as to the origin of the rapakivi texture. He places much weight on the occurrence of small crystals of idiomorphic quartz and other minerals, as constituents which have crystallized earlier than the orthoclase. He thinks that they bear witness to events earlier than the formation of the bigger feldspar crystals. The orthoclase also occurs in two generations. He emphasizes the individuality in the behaviour of the greater feldspar crystals, the development of which is, in a certain way, independent of that of the other minerals. As to the explanation of the rounded form of the feldspar ovoids, Wahl refers to Tammann's observations, according to which rounded crystals are formed in metallic melts at very high temperatures.

Wahl thinks that the consolidation has taken place in two different stages. Orthoclase crystals which were formerly consolidated were changed, by more or less complete r e f u s i o n, into a kind of d r o p s. Two or more crystals could then occasionally blend into one. By the crystallization of the feldspar ovoids, a contraction of the rock took place, and orthoclase and quartz crystallized in the interstices.

The refusion is explained by an increase of pressure caused by the crystallization. As a consequence, cataclysmatic eruptions took place, the pressure was suddenly relieved and an isothermic refusion occurred. The gaseous constituents may have escaped intermittently.

Wahl's theory contains many new and suggestive ideas, but is geologically, as well as geophysically very complicated.

THE PRESENT AUTHOR'S FIRST EXPLANATION.

In the first description of the rapakivi granites by the present writer (77), he gave the following explanation of the rapakivi texture which is here given in translation: »The cause of this egg-, or perhaps better expressed, ovoidal shape of the phenocrysts seems very mysterious. Every thought of a resorption in so great a measure and with such regularity appears a priori untenable. Moreover, neither the outer rim, nor the inner rings ever show any cavities which might be ascribed to a corrosion, but have always regular shapes.

The ovoidal shape seems thus to have existed during all the time of the growth of the crystal. Could it, perhaps, be possible to think that the remarkable impurity of the orthoclase of these ovoids caused the material not to form crystals limited by plane surfaces, but individuals which were rounded, although (crystallographically) equally orientated?»

In the author's memoir on Migmatites, I, this reasoning was repeated and in concluding he said:

»The author regards the ovoids as imperfect crystals whose impurity accounts for the defective development of their crystal forms.»

It is thus a misunderstanding, when Wahl thinks that the present author has, in his first article on the rapakivi rocks, expressed the opinion that the rounded shape of the porphyritic feldspar may be caused by the fact that the rapakivi magma had assimilated foreign material as fragments and in this way become impure.

The author's theory gave a very incomplete explanation, as it was not accounted for in which way the impurity of the material caused the rounded shape of the feldspars.

THE AUTHOR'S MODIFIED EXPLANATION.

If the formation of the well rounded spheroids in orbicular granites is favoured by a high degree of viscosity, caused by a great amount of oligoclase in the surrounding magma, then a similar explanation may also be tentatively applicable to the rapakivi structure. In fact, only such crystals of orthoclase as are surrounded by a shell of oligoclase show the well rounded forms, while there may be found, in other varieties of the rapakivi granites, and even alongside the ovoidal crystals, such as possess no oligoclase rim, which are quite angular. Also in older granites, as well as in the palæozoic granites of the Oslo region, we occasionally find crystals of potash feldspar surrounded by an oligoclase rim, and then they also show a rounded shape.

Thus, there seems to be a causal connection between the occurrence of ovoidal feldspar and oligoclase rims. It is perhaps possible to assume that the zone of magma rich in oligoclase that has originated by the crystallization of the potash feldspars and not been removed at once by diffusion, has caused, by its high viscosity, an internal friction hindering the diffusion, and gradually causing the cessation of the crystallization of the potash feldspar. Therefore, spheroidal crystals instead of those with a perfect crystal form, have originated.

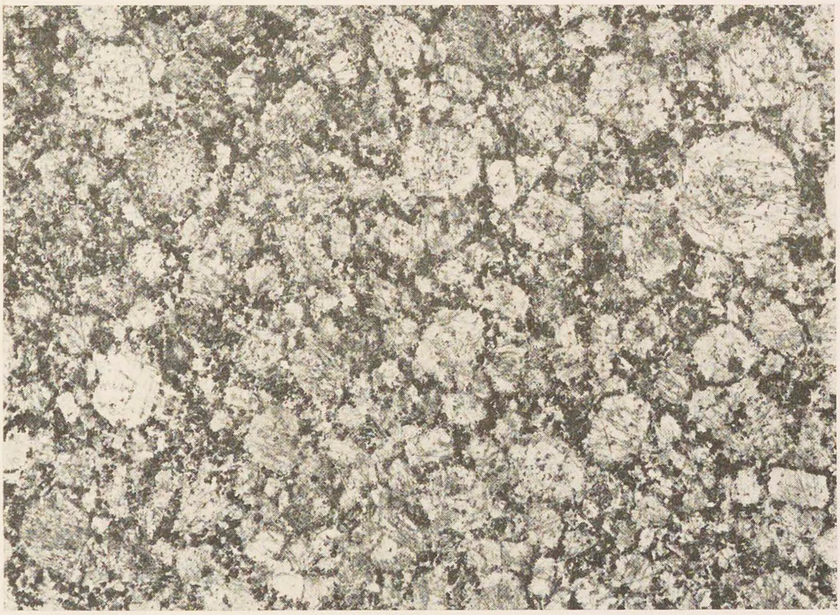


Fig. 17. Polished specimen of rapakivi from the harbour of Wiburg. 1/4 nat. size.

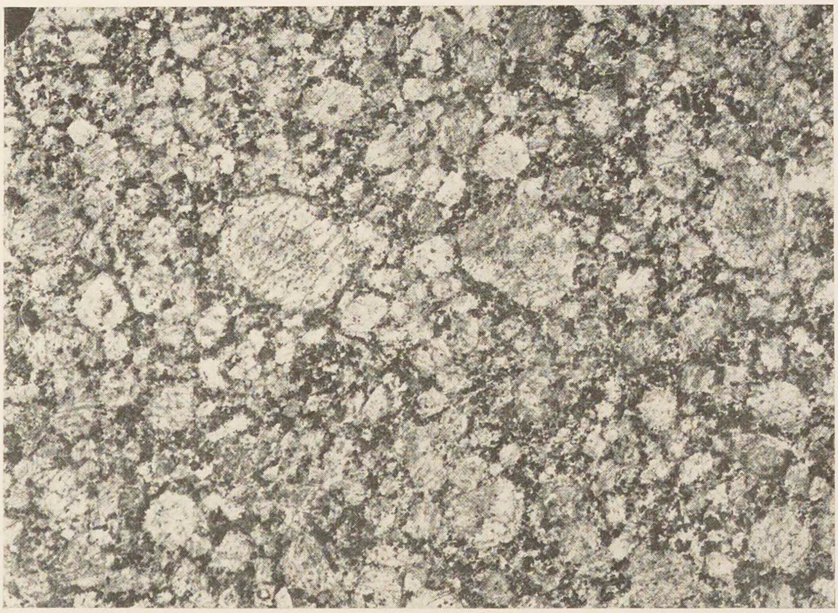


Fig. 18. Polished specimen of rapakivi from the harbour of Wiburg. 1/4 nat. size.

When regarding fig. 17—18, we are aware that those orthoclase crystals, which possess no rim of oligoclase, are quite angular. In fig. 2, plate XII, one orthoclase crystal is surrounded by a rim of oligoclase, around which we find, again, other shells consisting mainly of orthoclase. This feldspar may be designated as a small spheroid. The well rounded feldspar in the left part of fig. 18 also merits attention. It is composed of several concentric shells separated by zones rich in small inclusions of quartz and biotite. In general, the biggest of the well rounded feldspars may attain a size of 12 cm in diameter. In fig. 3, plate XII, we observe a feldspar which is also very big, but obviously has originated by the combination of several smaller feldspars. It has not the same crystallographical orientation all through, and is coated with oligoclase only at one side.

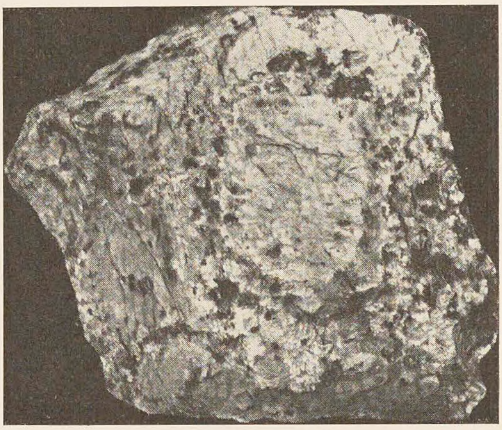


Fig. 19. Ovoid of orthoclase surrounded by oligoclase showing well developed crystal form. Rapakivi from Vilajoki in Säkkijärvi, W. of Wiburg. C:a 2/3 nat. size.

The feldspar ovoids are not always simple crystals, or regularly built twins, but sometimes aggregates of grains with more irregular orientation. The plagioclase of the rims shows, in most cases, but not always, a parallel orientation with the orthoclase.

When the oligoclase shell is thick and regular as in the specimen shown in fig. 19, the rounding of the orthoclase is often perfect. The surrounding oligoclase, again, shows, in this case, a fairly perfect crystal form. Also when the oligoclase shells are very thin, but continuous, as in the rock shown in fig. 1, plate XII, the rounding of the orthoclases may be perfect.

There seems to have been a long interval between the crystallization of the main part of the feldspars and that of the femic minerals which are, in general, late constituents. In the rapakivi of Southern Russia we observe, according to Luczizky (55) olivine, a strange constituent of a granite. In exceptional cases, it occurs in the rapakivi of the Wiburg area, too. It seems to indicate that a ultrabasic residual magma has been occasionally formed through fractionation at the end of the crystallization.

In granites where the oligoclase has been the first to crystallize, we never observe any ovoidal feldspars.

Among the rapakivi granites found as boulders on the S.E. shore of the Gulf of Bothnia, a variety occurs in which the plagioclase forms euhedral crystals that have crystallized earlier than the orthoclase, and are enclosed by that mineral. It is very remarkáble that the orthoclase of this rock does not show any rounded shape, but forms angular crystals. This rock may, in a certain way, be called an anti-rapakivi, although it has no rapakivi-like appearance.

Iddings already long ago emphasized the similarity of the rapakivi texture and certain orbicular structures, and thought that they may have had a similar origin (45), and Frosterus has also expressed a similar opinion (29).

There is a prevalent idea according to which a magma should always simultaneously pass through the same stages of development, indicating changes which have occurred all over it at the same time. No doubt, the formation of the big feldspar ovoids of the rapakivi granite really belongs to a definite stage of the crystallization of the magma. This is clearly proved by the fact that rounded aggregations of grains of feldspar and quartz may be surrounded by coatings of orthoclase and plagioclase in which the individual grains possess the same diameter as in the feldspar ovoid.

On the other hand, we notice, when regarding surfaces of rapakivi rocks (cf. the figures), the great individual differences of many of the feldspar ovoids, showing that local differences in the conditions of the mineral formation have existed. Thus, it is necessary not to apply the idea of definite stages in the crystallization all over the magma too schematically.

At first, this explanation of the rapakivi texture here offered seems to be at variance with the explanation given of the porphyritic texture, and, in general, of granitic textures. It was assumed that the occurence of sparse centres of crystallization depended on a great fluidity of the magma, while a viscous character would cause the formation of a great number of smaller centres. In the present case, the feldspar crystals are very big, which should therefore indicate an easy transport of material from a vast tributary region.

However, the great size of the spheroids of the orbicular rocks also shows that, provided the same conditions of crystallization have long persisted, the material of a fairly large region of magma may occasionally gather around the same centre, although the magma has been viscous. Big crystals may, also, be formed in very viscous magmas, if the cooling is slow and gradual and the crystallization of

the same mineral goes on for a long time. As to porphyritic rapakivi rocks, it is not necessary to think that all the tributary region around each feldspar ovoid continuously possessed the same viscosity. On the contrary, the magma may have been rather fluid in the main, while only a narrow zone rich in oligoclase, heaped up during the crystallization of the orthoclase, was very viscous and prevented the latter from forming well shaped crystals.

The great richness of the rapakivi magma in fluor is a point of great importance, and may have influenced the fluidity of the molten orthoclase, as well as the crystallization of the hornblende and biotite, with which the fluorite is often associated. There may have been other circumstances modifying the crystallization processes, and the influence of the viscosity.

The analogy of the rapakivi ovoids with the smaller spheroids of the orbicular granites, and other phenomena observed in them, is so great that it seems possible that they have a common explanation. It must, however, be admitted that many important differences also exist between spheroids of orbicular rocks and the ovoids of the rapakivi. The present theory is therefore only offered as a suggestion, giving a hint as to one of the directions in which we may hope to find the true explanation.

FINAL REMARKS.

Viscosity is, of course, only one of the factors which condition the size of the grain in igneous rocks. That things are often very complicated is shown, e. g., by the great difference that granitic dyke rocks, pegmatites and aplites, show which have obviously been formed under very analogous conditions. Both may occur in the same dyke or vein. They have probably crystallized out of a magma rich in water vapour and other solvents. And anyhow the pegmatite belongs to the most coarse-grained rocks, while the aplite is usually medium-grained.

Of these rocks, pegmatite is the more typical dyke rock. When a broad straight fissure has been formed, it is more often filled with pegmatite than with aplite. When, again, older rocks have been ultrametasomatically changed into a granite, this palingenetic rock is more usually an aplite than a pegmatite.

It is clear that the crystallization must take place in a very different way in an open fissure and in rock masses where the old minerals are gradually replaced by those belonging to the aplite.

In general, in all rocks where crystalloblastic minerals are formed, whether by metamorphic or ultrametamorphic processes, the laws

determining their mode of crystallization are very different from those determining the crystallization of dry magmas, and therefore we must also expect that many deep-seated rocks, in the solidification of which autometamorphic processes so often have been concomitant, will behave very differently from those which have originated mainly by the cooling of a magma where no subsequent changes have taken place after or during crystallization.

Although the importance of viscosity has thus far certainly been underrated, the present writer desires to issue a warning against all exaggeration in the application of this idea.

At the time, twenty seven years ago, when attention was first called to the importance of viscosity in regard to the textures of igneous rocks, a theory was propounded in medical science which accounted for the origin of several diseases and morbid states by the viscosity of the blood, caused by its content of uric acid. Dr. Alexander Haig wrote a thick volume about that theory which became very popular among the great public and caused the appearance of a number of different systems of diet trying to keep the blood free from vitiating matters that added to its viscosity. This theory has not met with much approval on the part of medical men of science, and many of its adherents are regarded by them as faddists. There are many faddists also in natural science who, on the revelation of a new idea, try to apply it with zealous eagerness as extensively as possible. The present writer would not like to be regarded as a zealot for viscosity, although he thinks that its importance has thus far been underrated. However, he is fully aware of the fact that the problem of the solidification of igneous rocks is a complicated one, and cannot be solved from only one point of view.

Whatever may be said about the explanations here suggested, it is evident that the orbicular rocks, as well as the rapakivi, well deserve a continued and very detailed study. As Lawson justly remarks (51), the difficulty of the explanation of the former lies in the fact that it would be necessary to the investigator to combine the knowledge of an experienced petrologist and a physical chemist.

Nowadays, there exists a whole school of petrologists who are very thoroughly acquainted with physical chemistry, and are very apt to introduce its methods and conceptions into petrological questions. The orbicular rocks and especially their microstructures seem to offer a very good opportunity for such studies, and the present author heartily hopes that the interesting problems here discussed will also be taken up from that point of view and thus be brought nearer to their final solution. For those who contemplate such detailed studies, material will be easily available.

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M. ALFRED LACROIX has kindly given information about some little known Japanese orbicular granites, which are described in the following publication:

Preservation of Natural Monuments in Japan, issued by the Department of Home Affairs. Tokyo 1926. IV. Preservation of Geological and Mineralogical Natural Monuments in Japan, by Denzo Satò, p. 17—21.

Granite orbiculaire de Sanage-yama.

Dyke dans un granite à gros grain de 2 à 3 m d'épaisseur. Les sphéroides ont de 4 à 8 cm de diamètre, irréguliers ou elliptiques. Ils comprennent a) un noyau (2 à 5 cm) = quartz, orthose et biotite, b) une écorce (2 cm) = orthose, perthite, microcline, biotite, quartz, disposés radialement. La périphérie est à grain fin et passe progressivement à une structure pegmatique.

Granite orbiculaire de Minedera-yama.

Dyke 13 m 3 de largeur, 6 m de longueur dans granite porphyroide. Il est traversé par deux veines de pegmatite et renferme une enclave de hornfels.

Les sphéroides sont aplatis (11 cm × 4.8 cm). Noyau noir (biotite avec auréoles polychroiques, quartz, apatite, zircone) et écorce (cordierite disposée radialement, sillimanite, corindon, oligoclase, muscovite, biotite). Les sphéroides ont une texture rubanée, avec alternance de lits blancs, quartzeux, et de noirs (biotite). Parfois le noyau manque.

Granite orbiculaire de Kenashi-yama.

Ce granite globulaire (6 m d'épaisseur), est une portion d'un gneiss à biotite et à hornblende auquel il passe. Les sphéroides (7 cm à 4 cm) ont un centre à grain fin de feldspaths, biotite et hornblende, avec ou sans un noyau de feldspath et une écorce (orthose, plagioclase, hornblende, biotite, avec sphéne, apatite, zircon, minérais comme minéraux accessoires). La structure radiale et concentrique est souvent très nette. Les nodules peuvent être extraits de leur gangue. D'une façon générale les sphéroides sont plus basiques que le reste de la roche qui a la même composition qualitative.

Besides the rocks mentioned, an orbicular diorite from Otakasawa in the prefecture of Miyagi is also described in the same publication (pl. XXI).

DESCRIPTION OF THE PLATES.

Plate I, fig. 1. Orbicular granite from the island of Puutsaari in the parish of Jaakkima, on the northern shore of Lake Ladoga. $^1/_3$ nat. size.

Fig. 2. Surface of a rock of orbicular granite N.E. of Lake Nuoks Långträsk in the parish of Esbo, N.W. of Helsingfors. C:a $^1/_6$ nat. size.

Plate II, fig. 1. Polished specimen of orbicular granite from Esbo. C:a $^1/_8$ nat. size.

Fig. 2. Horizontal surface of a rock of orbicular granite in Esbo; shows an included fragment of metabasite, surrounded by an aureole formed through resorption.

Plate III, fig. 1. Horizontal surface in rock of orbicular granite at Nuoks Långträsk in Esbo. Variety with small spheroids in contact with the variety with bigger spheroids. $^1/_6$ nat. size.

Fig. 2. Fragment of a migmatitic gneiss in which some small spheroids have been formed. Nuoks Långträsk, Esbo. $^1/_{10}$ nat. size.

Plate IV, fig. 1. Polished specimen of orbicular granite (variety with small spheroids) from Kuohenmaa in the parish of Kangasala, S.E. of Tampere (Tammerfors). C:a $^1/_4$ nat. size.

Fig. 2. Polished specimen of orbicular granite from Kivikangas, in the parish of Hankasalmi, N. W. of Mikkeli (St. Michel). $^1/_4$ nat. size.

Plate V, fig. 1. Polished specimen of orbicular granite (variety with big spheroids) from Kangasala. C:a $^1/_7$ nat. size.

Fig. 2. Polished specimen of orbicular granite from Hankasalmi. C:a $^1/_{12}$ nat. size.

Plate VI, fig. 1, A, B, C. Specimen of the orbicular granite from Kangasala, showing nuclei of different character. C:a $^1/_3$ nat. size.

Fig. 2. Polished specimen of orbicular granite of Kangasniemi, showing an ellipsoid with a nucleus consisting of a fragment of a foreign rock. $^2/_9$ nat. size.

Fig. 3. Polished specimen of orbicular granite from Kangasniemi, showing cement with pegmatitic structure. C:a $^1/_5$ nat. size.

Plate VII, fig. 1. Polished specimens of orbicular granite from Virvik in the parish of Borgå, to the left with very imperfect spheroids, in the middle with somewhat better developed and to the right with well developed ones. C:a $^1/_{12}$ nat. size.

Fig. 2. Polished specimen of the orbicular granite from Virvik, variety with small spheroids. C:a $^1/_4$ nat. size.

Plate VIII, fig. 1. Orbicular granite from Virvik (variety with small spheroids) as partly dissolved fragments in a dyke-like granitic mass, polished specimen. $^1/_5$ nat. size.

Fig. 2. Orbicular granite from Virvik, polished specimen (owned by Dr V. Hackman) showing strong deformations of the spheroids. Ca: $^1/_5$ nat. size.

Plate IX, fig. 1. Orbicular granite showing many big and one small spheroid, a cement with differentiated sialic and femic portions, and strong deformations of the spheroids. Polished specimen from Virvik, Borgå. C:a $^{1}/_{5}$ nat. size.

Fig. 2. Strongly deformed spheroids with layers deposited unconformably upon eroded layers. Polished specimen from Virvik, Borgå. $^{2}/_{9}$ nat. size.

Plate X, fig. 1. Spheroid showing deformation by torsional movement. Polished specimen from Virvik, Borgå. $^{2}/_{9}$ nat. size.

Fig. 2. Spheroid showing pseudopodium-like projections. Polished specimen from Virvik, Borgå. $^{2}/_{5}$ nat. size.

Plate XI, fig. 1. Schistose rock with veins of aplitic granite, both containing nodules of quartz and sillimanite. Horizontal rock surface on the island of Stor-Klyndan in the parish of Kumlinge among the Åland Islands. C:a $^{1}/_{10}$ nat. size.

Fig. 2. Nodule of quartz, plagioclase etc. in a mica-schist on the island of Tulola, near Sortavala, in Lake Ladoga. C:a $^{1}/_{7}$ nat. size.

Plate XII, fig. 1. Rapakivi in a horizontal rock surface on the island Mäntysalo (Laatinsaaret), Vehkalahti, N.E. of Kotka. C:a $^{1}/_{7}$ nat. size.

Fig. 2—3. Polished specimens of rapakivi from Wiburg (Viipuri), near the harbour. $^{1}/_{3}$ nat. size.

Plate XIII, fig. 1. Cement of the orbicular granite from Puutsaari, showing deuteric muscovite, containing calcite in the middle and included in microcline. 15 ×. Nicols +.

Fig. 2. Shell of a spheroid in the granite from Puutsaari. 7 ×. Nicols +.

Fig. 3. Oligoclase crystals with dentated outlines in the orbicular granite with small spheroids from Nuoks Långträsk in Esbo. 7 ×. Nicols +.

Fig. 4. Microcline which is entirely xenomorphic towards oligoclase, in a nucleus of the orbicular granite with big spheroids from Esbo. 12 ×. Nicols +.

Fig. 5. Microcline containing numerous inclusions of oligoclase, when bordering on bigger crystals of oligoclase. Nucleus of a spheroid in the granite of Esbo. 14 ×. Nicols +.

Fig. 6. Quartz which is entirely xenomorphic towards oligoclase. Nucleus of a spheroid in the granite of Esbo. 22 ×. Nicols +.

Plate XIV, fig. 1. Shell of a spheroid in the orbicular granite of Esbo. 10 ×. Nicols +.

Fig. 2. Oligoclase containing inclusions of microcline (in the middle) and biotite (coating the walls). 13 ×. Nicols +.

Fig. 3. Oligoclase with appendix of myrmekite. Cement of the orbicular granite of Esbo. 20 ×. Nicols +.

Fig. 4. Antiperthitic implication of oligoclase and microcline. Cement of the orbicular granite of Esbo. 15 ×. Nicols +.

Fig. 5. Biotite which is entirely xenomorphic towards oligoclase. Cement of the orbicular granite of Esbo. 20 ×. Nicols +.

Fig 6. Biotite which shows a fringed margin towards oligoclase. Cement of the orbicular granite of Esbo. 20 ×. Nicols +.

Plate XV, fig. 1. Radially arranged crystals of oligolase, next to a biotitic shell, below wich appears a part of the nucleus, consisting of a schistose rock rich in biotite. Orbicular granite from Kangasala (with smaller spheroids). 7 ×. Nicols +.

Fig. 2. Oligoclase crystals arranged radially, surrounding a nucleus of biotite. Orbicular granite from Kangasala (with smaller spheroids). 10 ×. Nicols +.

Fig. 3. Shells of spheroid in the orbicular granite of Kangasala (with bigger spheroids), showing unconformable deposition of minerals. 6 ×. Nicols +.

Fig. 4. Shells of spheroids in the orbicular granite of Kangasala (with smaller spheroids), showing disturbances of the position of certain biotite crystals. 7 ×. Nicols +.

Fig. 5 and 6. Shells of spheroids in the orbicular granite of Kangasala (with smaller spheroids) showing »warp and weft» texture. 7 ×. Nicols +.

Plate XVI, fig. 1. Shell of a spheroid of the orbicular granite of Kangasala (with small spheroids), showing »warp and weft» texture. 7 ×. Nicols +.

Fig. 2. Muscovite as a deuteric constituent, which has replaced feldspar, in the cement of the orbicular granite of Kangasala (with big spheroids). 10 ×. Nicols +.

Fig 3. Biotite showing skeletal forms and surrounded by quartz, in the cement of the orbicular granite of Kangasala (with small spheroids). 10 ×. Nicols +.

Fig. 4. Cement of the orbicular granite of Kangasala (with small spheroids) showing idiomorphic biotite, oligoclase and xenomorphic microcline and quartz. 7 ×. Nicols +.

Fig. 5. Mortar structure in the microcline of the orbicular granite from Hankasalmi. 6 ×. Nicols +.

Fig. 6. Shell of the orbicular granite from Hankasalmi, showing a texture affected by metamorphic changes. 12 ×. Nicols +.

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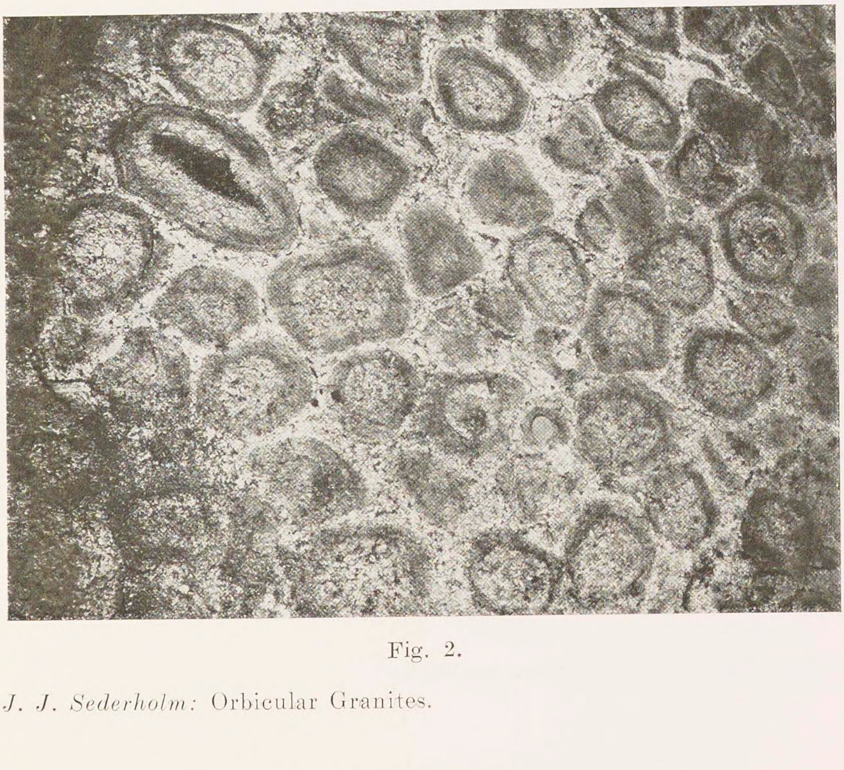
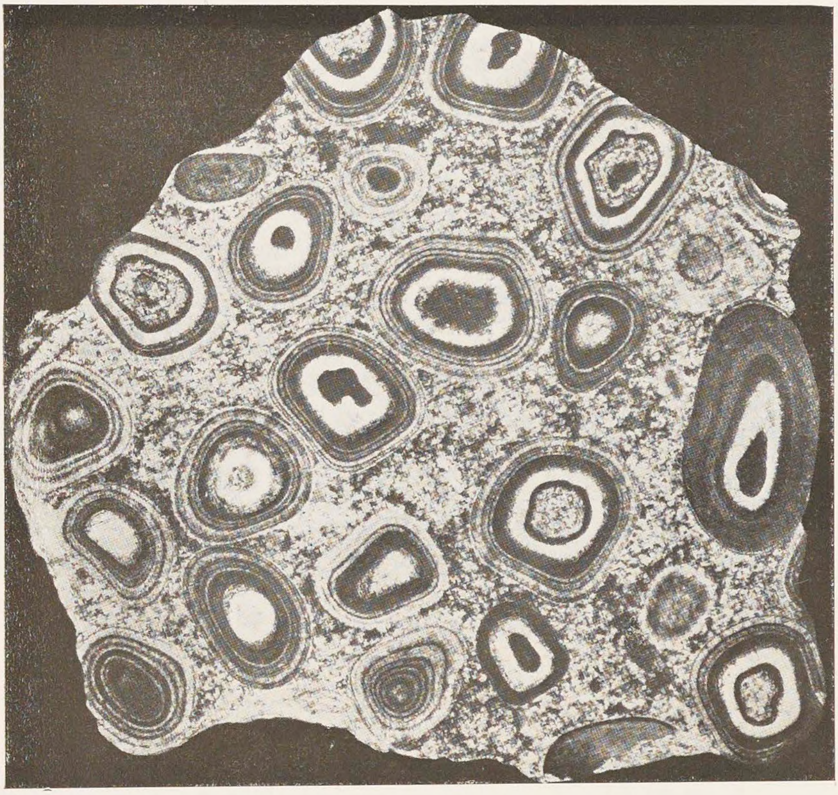


Fig. 2.

J. J. Sederholm: Orbicular Granites.



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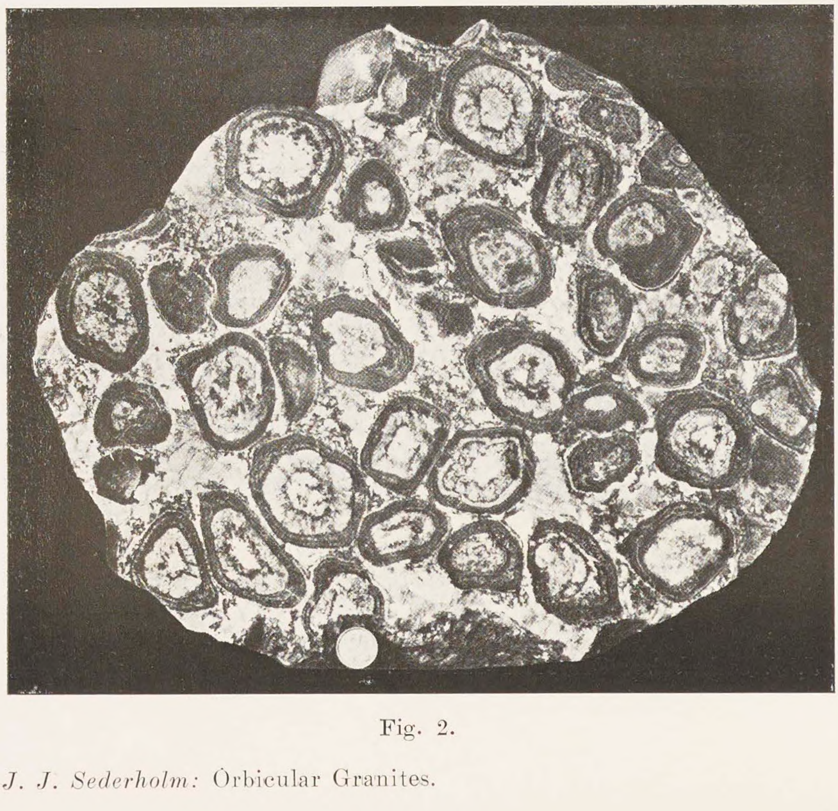

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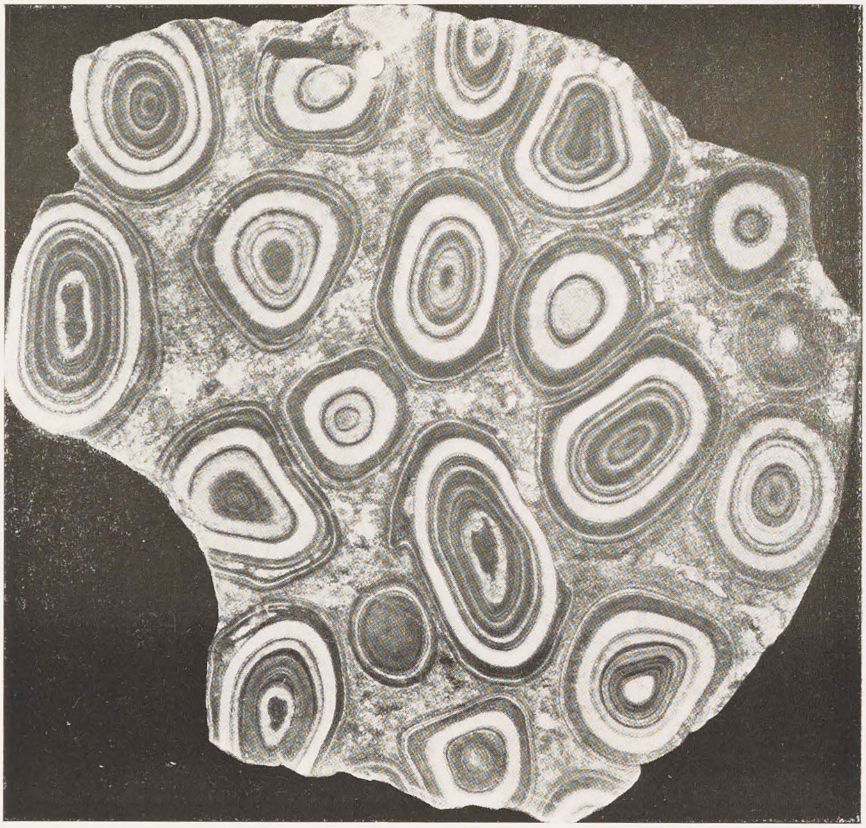

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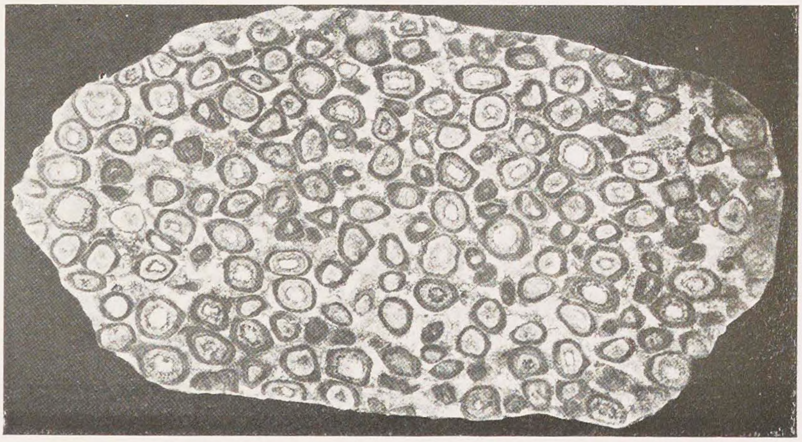

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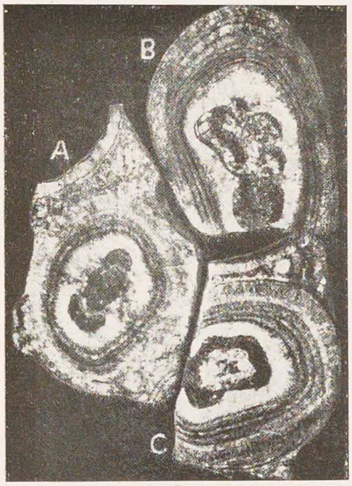

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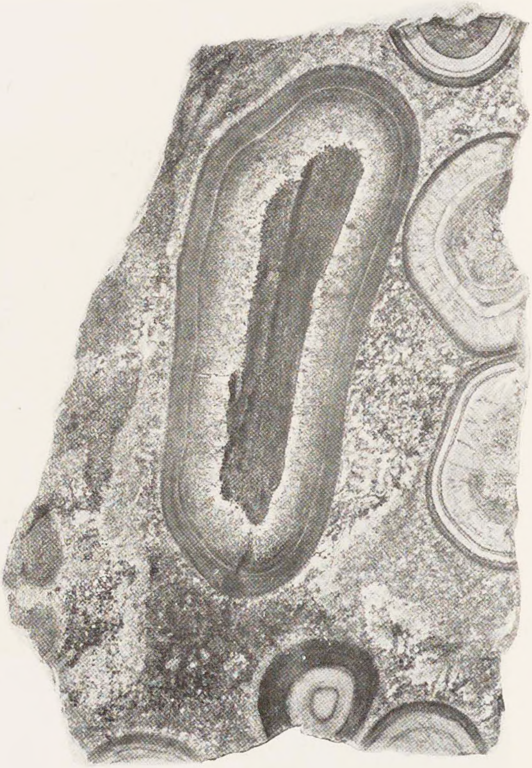

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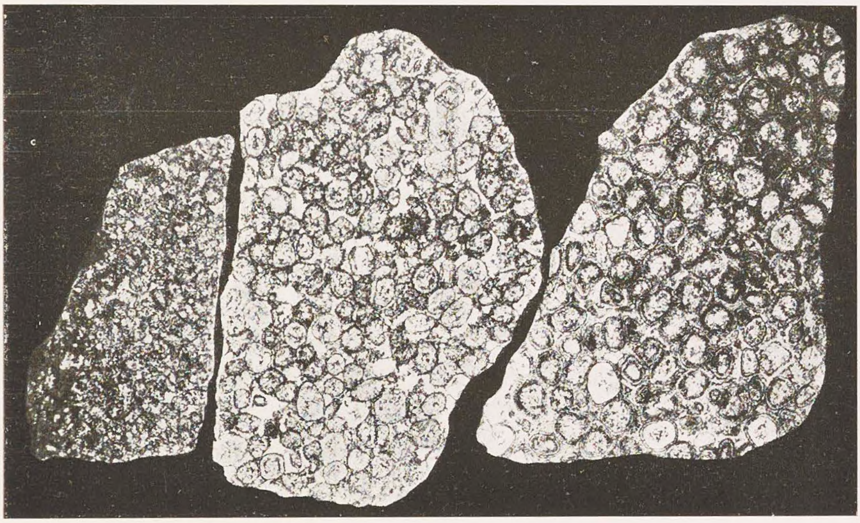

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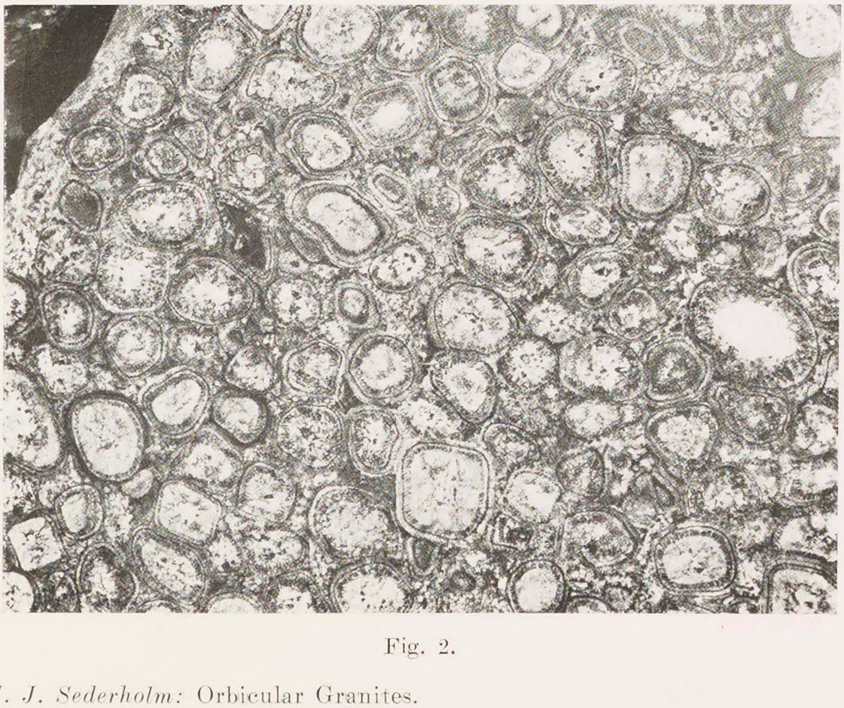

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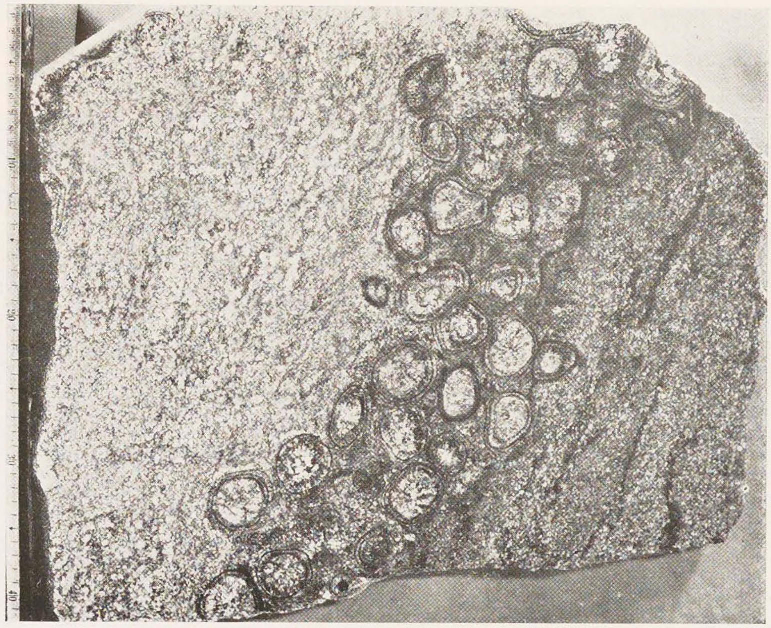

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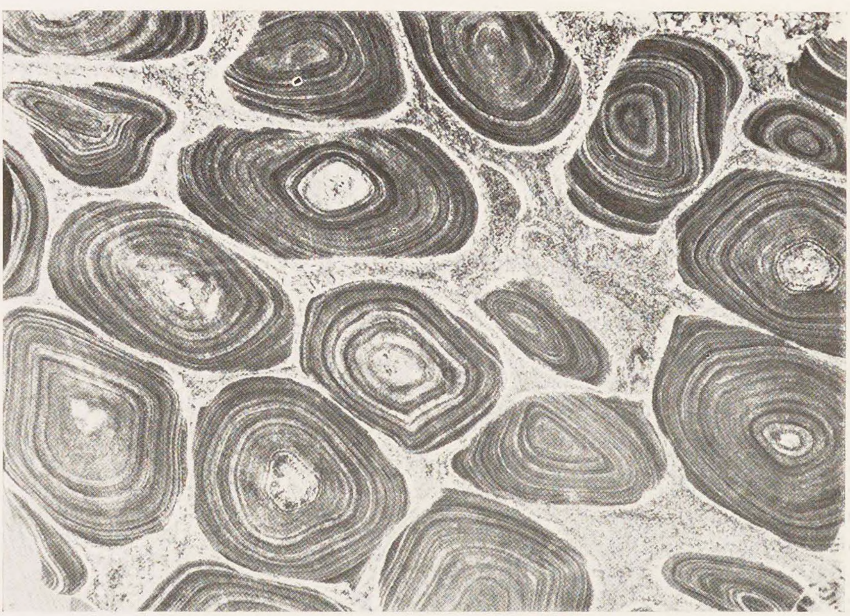

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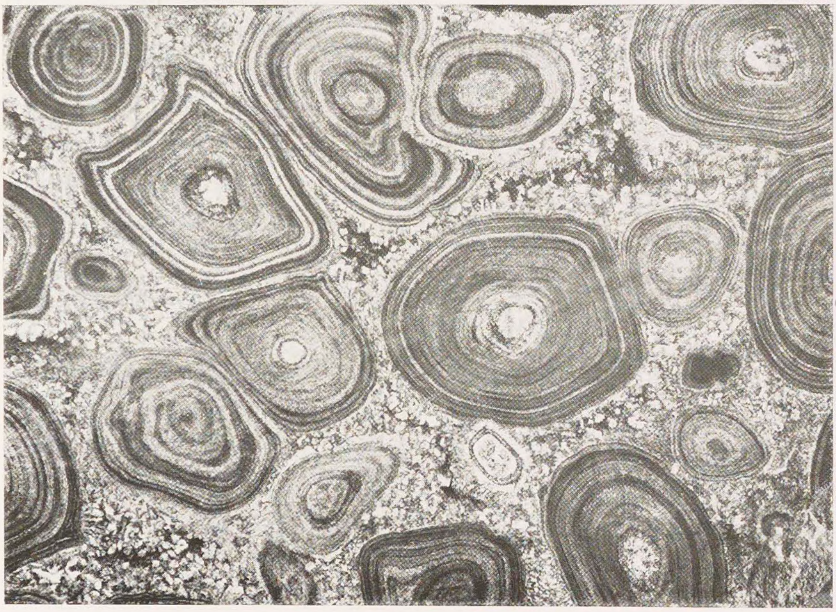

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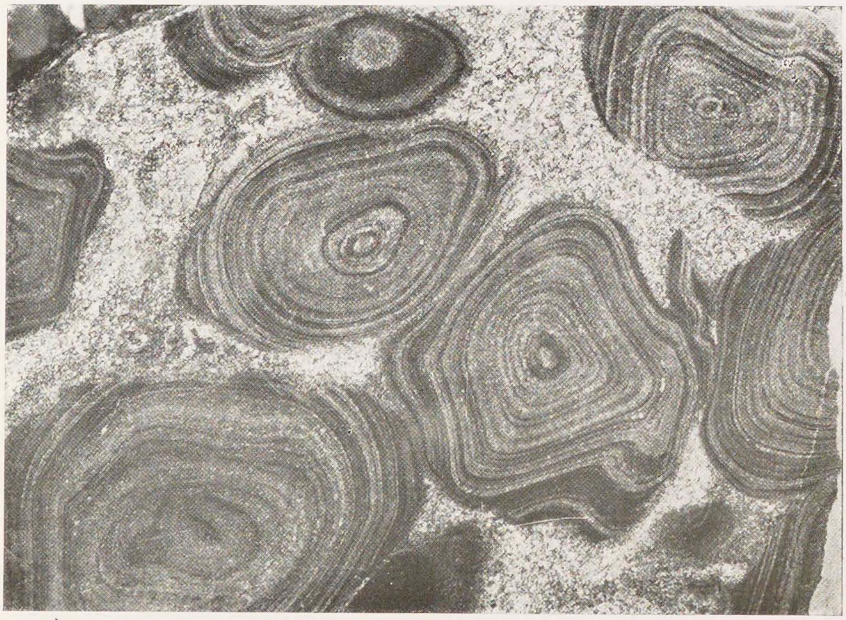

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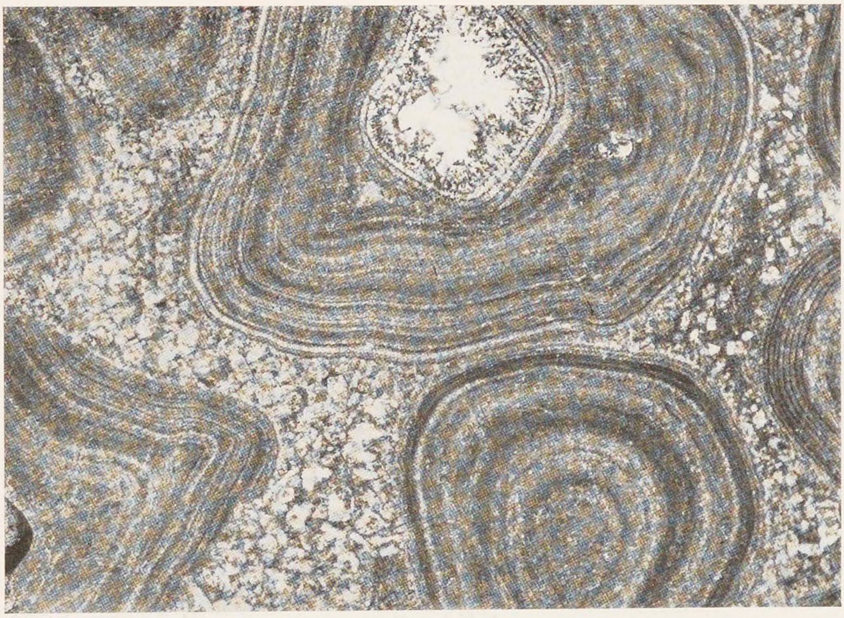

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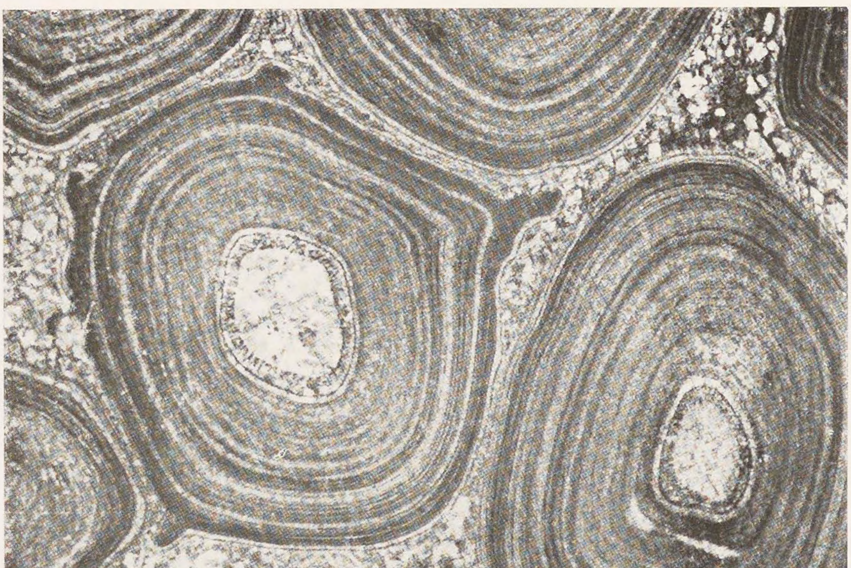

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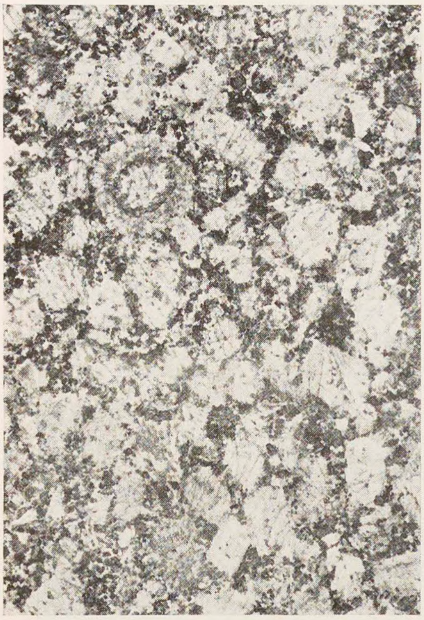

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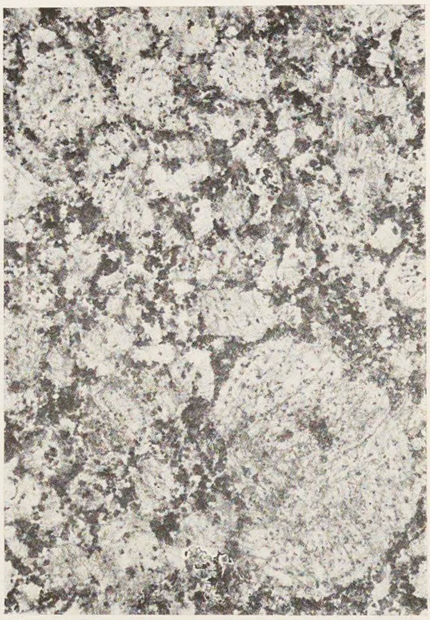

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J. J. Sederholm: Orbicular Granites.

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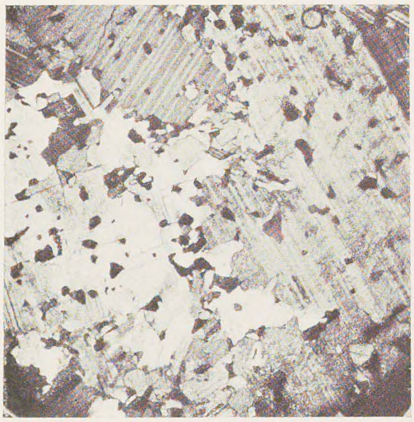

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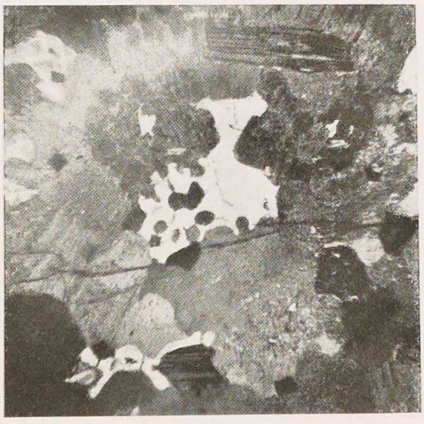

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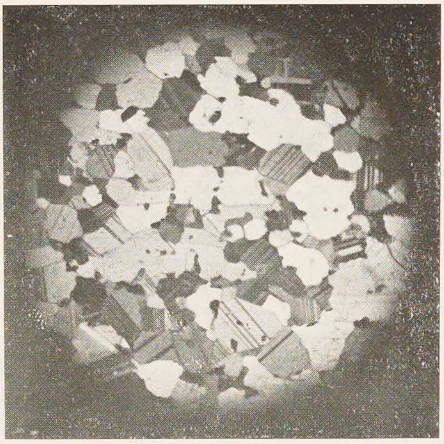
J. J. Sederholm: Orbicular Granites.



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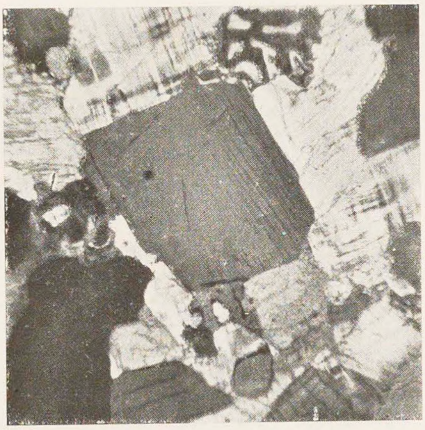

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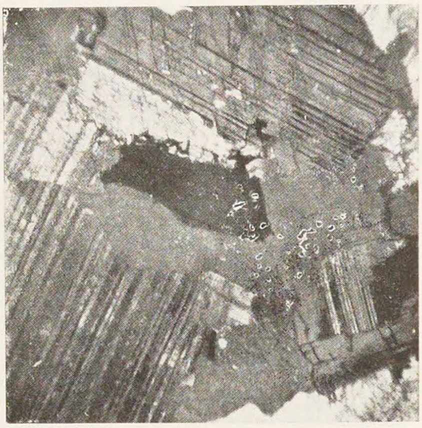

Fig. 6.

J. J. Sederholm: Orbicular Granites.

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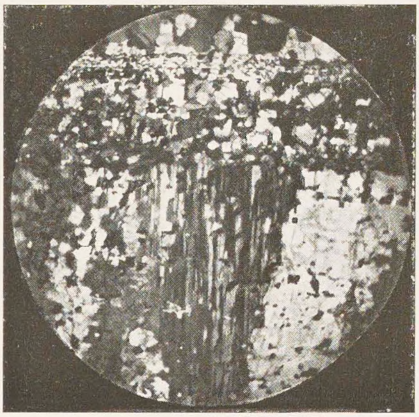

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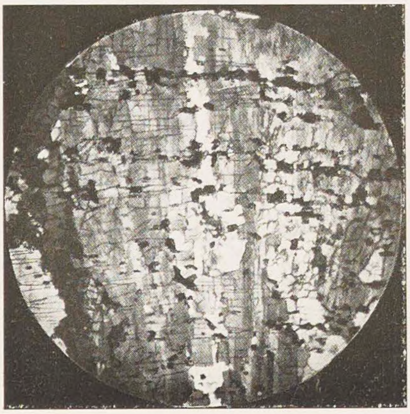

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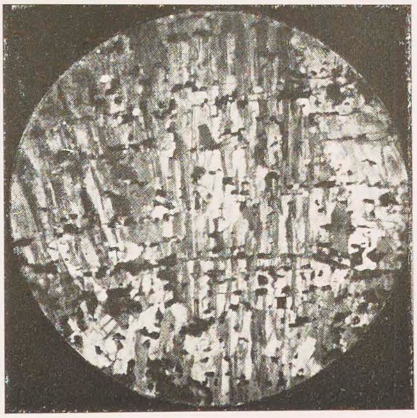

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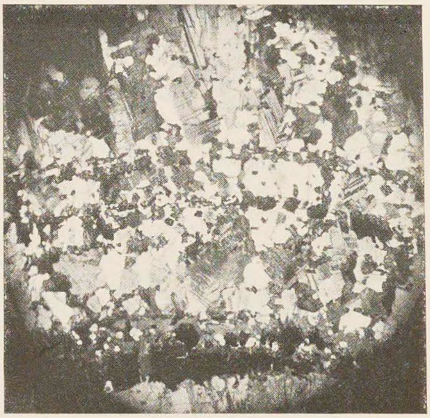
J. J. Sederholm: Orbicular Granites.



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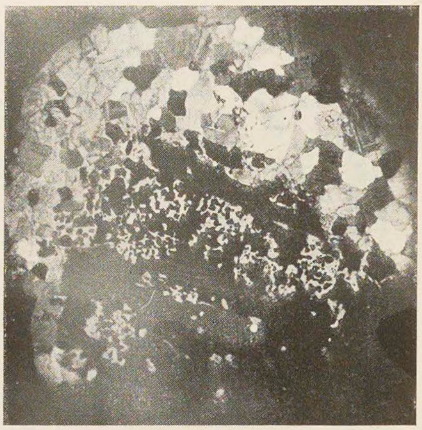

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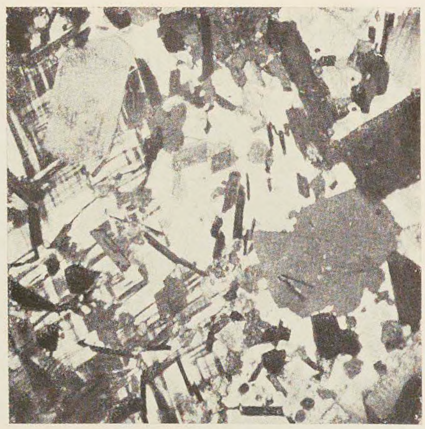

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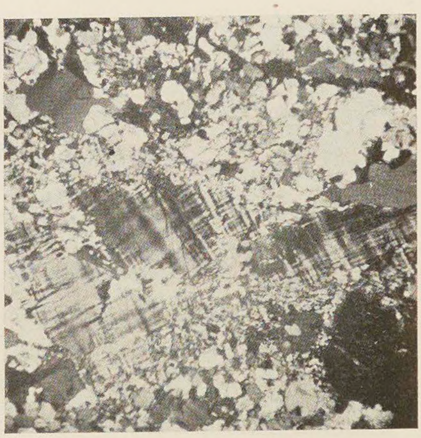

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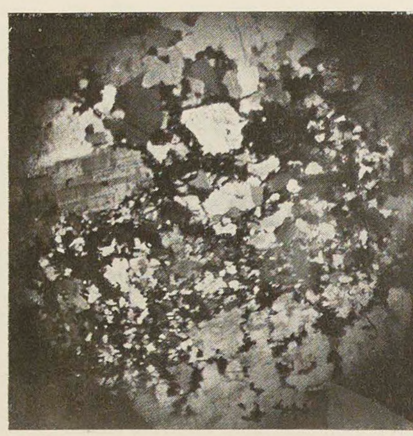

Fig. 6.

J. J. Sederholm: Orbicular Granites.

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* Epuisée.

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